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Larsen, Torben J.; Astrup, Poul

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Influence on surfers wind conditions east of the new Hanstholm harbour/wind turbine project

Torben J. Larsen and Poul Astrup

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Author: Torben Juul larsen, Poul Astrup

Title: Influence on surfers wind conditions east of the new Hanstholm harbour/wind turbine project

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Abstract:

In this report a consequence study regarding the surfers wind conditions east of the planned new harbour area of Hanstholm. At this harbour area, 10 new 150m tall 3MW wind turbines are planned. Both the harbour constructions as well as the wind turbines could potentially alter the wind conditions on the lee side, which is an important area for wind and kite surfers.
In this study, both changes in mean wind velocities as well as the turbulence level are investigated for the surf area between a location called "Fish Factory" to the location called "Hamburg". The interesting wind speed interval is 8-16m/s mainly from west, measured in 10m height. Results are extracted in several downstream locations specified by Grontmij covering the area used for surfing.
It is expected that surfing mainly occurs for wind speeds above 10m/s (10m height) and the important parameters both level of mean wind speeds as well as low turbulent conditions within the surf area.
In general the impact of wind turbine wake is very limited in the eastern part of the surf area, whereas a reduction in mean wind speed in combination with increased turbulence intensity is seen in the western area.

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Technical University of Denmark
DTU Wind Energy
P.O.Box 49
4000 Roskilde
Denmark
Telephone +45 4677 5085
savi@dtu.dk

Contents

1 Preface and general conclusion

This report presents a consequence study regarding the surfers wind conditions east of the planned new harbour area of Hanstholm. At this harbour area, 10 new 150m tall 3MW wind turbines are planned. Both the harbour constructions as well as the wind turbines could potentially alter the wind conditions on the lee side, which is an important area for wind and kite surfers.

The Dynamic Wake Meander Model (Larsen et al., 2008b), (Madsen et al., 2010) and (Larsen et al., 2012) is used to investigate the wind conditions east of the planned new turbines at Hanstholm. This model, which predicts instationary wind conditions behind one or more wind turbines, has previously been used to predict the changed power and load conditions for wind turbines in wind farm conditions. A very fine agreement to measurements is seen and the model is therefore considered suitable for this particular study also.

In this study, both changes in mean wind velocities as well as turbulence levels are investigated for the surf area between a location called ”Fish Factory” to the location called ”Hamburg”. The investigated wind speed interval is 8-16m/s mainly from west, measured in 10m height. Results are extracted in several downstream locations specified by Grontmij covering the area used for surfing.

The tool LINCON and SHELTER from the WAsP engineering complex is used to study the wind effects from building and the general harbour area. Effects on mean wind as well as turbulence levels are estimated.

It is expected that surfing mainly occurs for wind speeds above 10m/s (10m height) and the important parameters including both level of mean wind speeds as well as low turbulent conditions within the surf area.

In general the impact of wind turbine wake is very limited in the eastern part of the surf area, whereas a reduction in mean wind speed in combination with increased turbulence intensity is seen in the western area.

The general conclusions are that the eastern part of the surf area is only affected to a minimal extent. In the western area an impact from both harbour construction as well as wind turbines in terms of decreased wind speed in combination with an increased turbulence level is seen. The level of these disturbances is highly dependent of both wind speed level and especially wind direction.

The impact from the wind turbines is mainly occurring for wind speeds below 10m/s, whereas only minor impact is seen for higher wind speeds. The reason for this is the wind turbine power control, which causes the turbine to produce highest possible at low wind speed and only partially for high wind speeds. The disturbed conditions are highly dependent on wind direction, where modified conditions are seen partially in the surf area with directions ranging from 270 to 300°. 285° is worst case. At 315° the new conditions corresponds fully to the existing conditions except for a small corner in the south west part. In general the reduction in mean wind speed is below 10%. The increase in turbulence is in worst case 50%, but above 12m/s the increase is hardly noticable.

It is expected that the impact from the wind turbines could potentially be reduced for the wind speed and directions impacting the surf conditions by operating all (or some of) the turbines in reduced power mode as part of a sector management control. The impact of such control was, however, not part of this study.

The shelter effect from the harbour construction area is more independent of the mean wind speed compared to the wake effect from the turbines. Worst wind direction is 270°. The maximum reduction is calculated for the south-western most point, for westerly wind, reaching 18%

15m above sea in the south-west corner of the surf area. At lower heights, the largest reduction in the western part of the surf area is about 10% whereas the reductions in the eastern area is around 3%. For the turbulence, an estimate based on an exponential probability density function for the wind speed deficit in the wake is that for an N% mean wind speed reduction the standard deviation for the wind speed fluctuations due to the wake becomes N% of the mean wind.

In order to investigate how the combined effect of shelter and wind turbine wakes would be time simulations of turbine wake and building generated turbulence was added in time domain. If the ambient turbulence is increase by 6% (due to the shelter induced turbulence level) and the turbulence from the turbines also increase by 6%, the final turbulence intensity is increased by 8%, hence the turbulence levels should be added together as a square root summation.

2 Description of the harbour plan

An extension of the existing harbour area is planned east of the present smaller harbour. In conjunction with this expansion, the idea is also to use the infra structure to mount 10 new 3MW wind turbines. The hub height of these turbines is expected to be 94m and with rotor diameter of approximately 112m. At the present there are both buildings and windturbines close to the surf area. These existing turbines which are planned to be taken down, consist of 4 DANmark 525kW turbines with 41.5m hub height and a rotor diameter of 37m. It is possible to see the location of these turbines in Figure 1 (turbine shadow captured by google), but they are more clearly seen in Figure 2.

Figure 1. Overview of harbour plan and area used for kite and windsurfing.

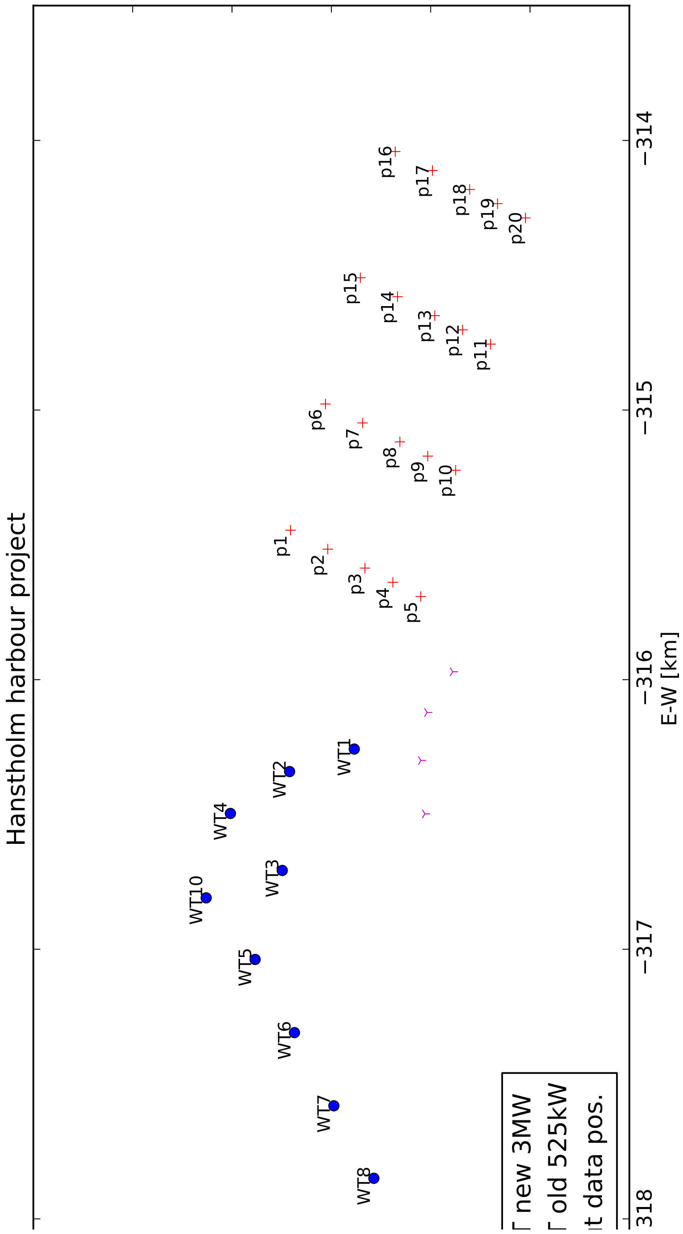

Figure 2. Plot of wind turbine positions and data output locations with numbering, used for wake study.

3 Impact from harbour constructions

Using the LINCOM and SHELTER programs from the WASP Engineering complex, (Mann et al.,), the effect of the new harbor areas, piers and buildings are calculated. Neither existing nor planned wind turbines are included in this part of the study. LINCOM calculates the perturbations that elevation and surface roughness changes make in an otherwise homogeneous wind field. SHELTER calculates the wind speed reduction in given points caused by upstream obstacles. LINCOM and SHELTER are described in detail in (Astrup and Larsen, 1999).

Surface roughness influences the wind profile. With a low surface roughness, the wind speed gradient is large near the surface, with increasing roughness as this gradient decreases. After a transition from one roughness to another, the wind profile changes from that in equilibrium with the upstream roughness towards that in equilibrium with the downstream roughness, starting the adaptation at the ground and slowly developing upwards.

Sheltering is well known. On the lee side of a shelter, there is no or almost no wind, but at some distance it picks up again and often irregularly, i.e. with increased turbulence.

3.1 Calculation procedure

First - using LINCOM - the wind field over the windsurfing area as influenced by the existing harbor is calculated, figure 3 and 5, next, as concrete has a very much higher roughness than water, the effect of the concrete area of the planned harbor extension is taken into account, again using LINCOM, figure 4 and 6, and finally, with the SHELTER program, the shadow effect of the existing and new piers and buildings are found. Where LINCOM determines the flow field for a regular grid over an area, figures 5 and 6, SHELTER determines the sheltering effect in a number of discrete points. The results are therefore for the designated 20 points in the windsurfing area and here given as the reduction in wind speed as a percentage of the wind in these points. The point values are further interpolated to the area between the points and presented as contour plots. Calculations have been made for the flow directions 240, 255, 270, 285, 300, and 315 degree, i.e. south-westerly to north-westerly wind, and for the heights 5 to 50 m with 5 m intervals. Only 5, 15, 25, and 35 m results are presented. Figures 7 to 12 contain the contour plots of the relative speed reductions for the four wind directions, and each figure contains plots for all four heights. The axes of the matrix of target points are approximately 20 degree off with respect to east/north, for which reason the axes of these plots just show the distances from the south-westernmost target point. The calculated perturbations due to the increased surface roughness and the speed reduction due to sheltering are all proportional to the incoming flow, so the wind speed change given as a percentage of the flow with the existing harbor does not depend on the incoming wind speed. All calculations are therefore made with the same incoming wind, here 10 m/s at 10 m above sea.

3.2 Conclusion on harbour sheltering

It is in all cases seen that the relative speed reduction is highest at 15 to 25m above sea and that it is highest for 270° wind direction, falling for more northerly winds and negligible for most of the area for wind directions above 315°. The maximum reduction is calculated for the south-westernmost target point, for westerly wind, reaching 18% 15m above sea in the south-west corner of the surf area. For the turbulence, an estimate based on an exponential probability density function for the wind speed deficit in the wake is that for an N% mean wind speed reduction the standard deviation for the wind speed fluctuations due to the wake becomes N% of the mean wind.

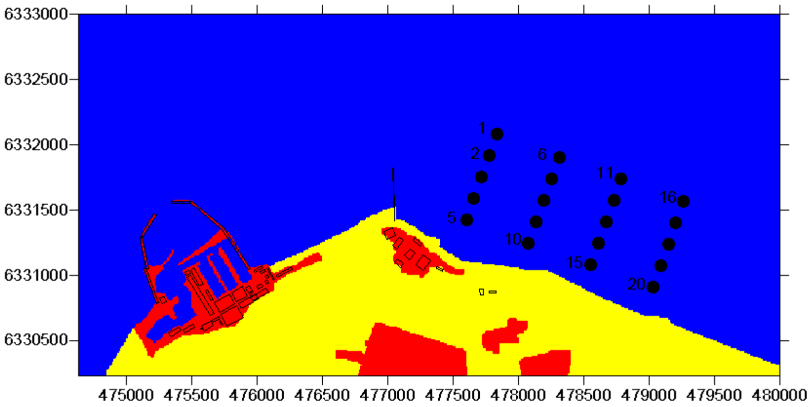

Figure 3. LINCOM calculation area with existing harbor plus ground polygons for existing piers and buildings as used by SHELTER. Red color indicates harbor and built up areas. The 20 points in the windsurfing area are indicated.

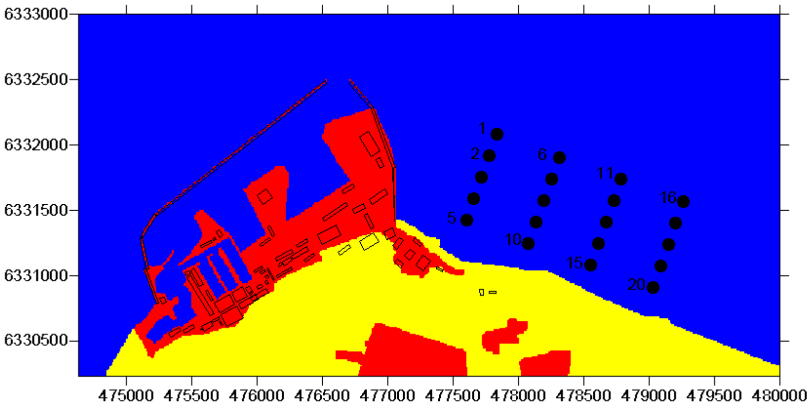

Figure 4. LINCOM calculation area with extended harbor plus ground polygons for new piers and buildings as used by SHELTER.

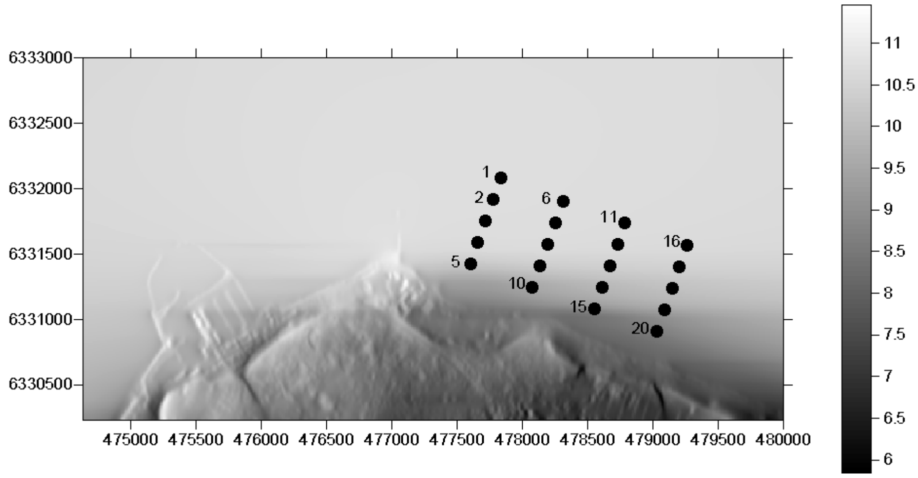

Figure 5. Wind speed picture [m/s] at 15 m above sea, wind direction 270 degree, existing harbor. Incoming wind: 10 m/s at 10m above sea.

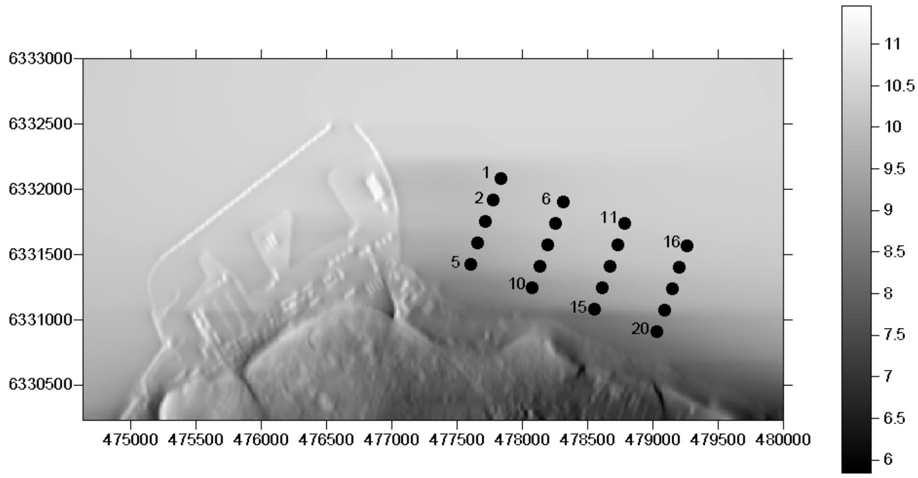

Figure 6. Wind speed picture [m/s] at 15 m above sea for wind direction 270 degree, extended harbor, but without sheltering effect of new buildings and piers. Incoming wind: 10 m/s at 10m above sea.

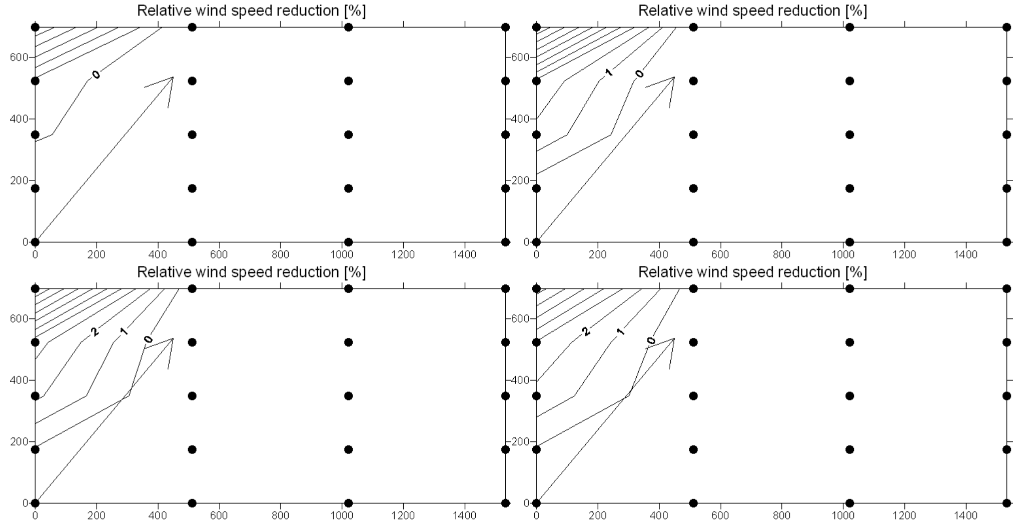

Figure 7. Wind speed reduction [%] at four heights above sea, 5m (upper left), 15m (upper right), 25m (lower left), and 35m (lower right) as interpolated between the 20 calculation points. Wind direction 240 degree, indicated by the arrow.

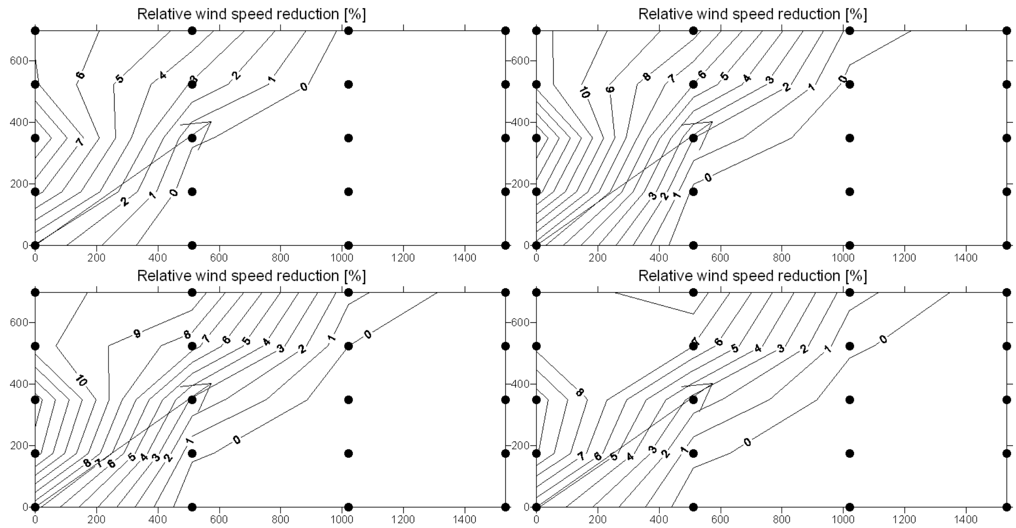

Figure 8. Wind speed reduction [%] at four heights above sea, 5m (upper left), 15m (upper right), 25m (lower left), and 35m (lower right) as interpolated between the 20 calculation points. Wind direction 255 degree, indicated by the arrow.

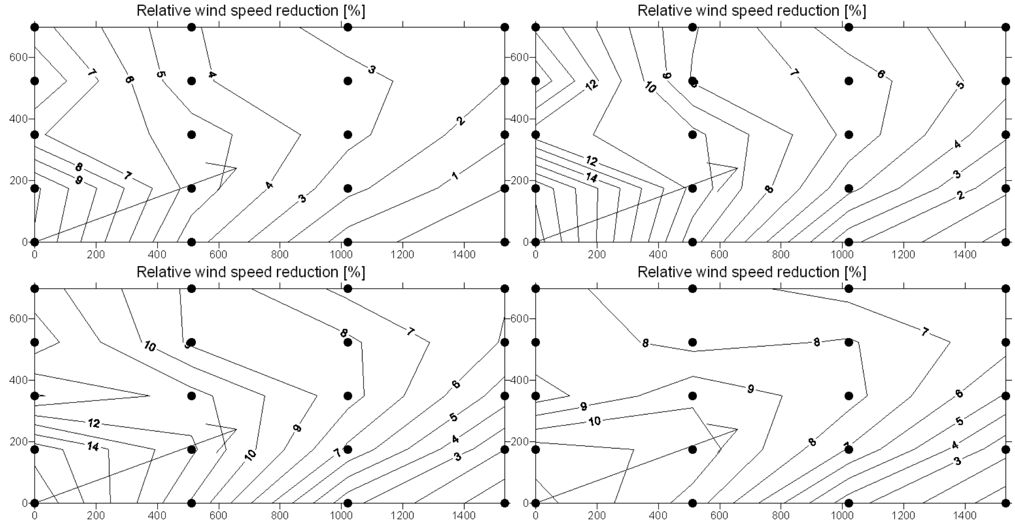

Figure 9. Wind speed reduction [%] at four heights above sea, 5m (upper left), 15m (upper right), 25m (lower left), and 35m (lower right) as interpolated between the 20 calculation points. Wind direction 270 degree, indicated by the arrow.

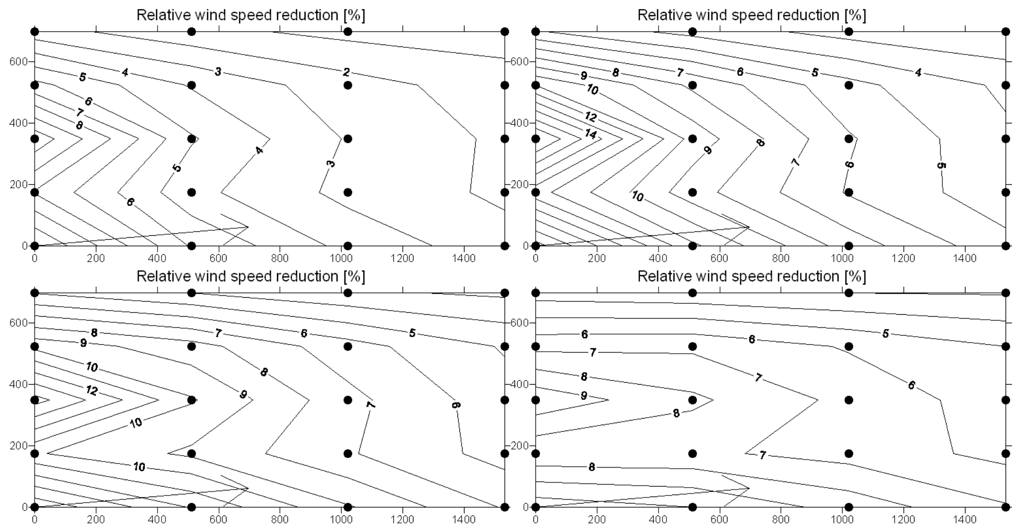

Figure 10. Wind speed reduction [%] at four heights above sea, 5m (upper left), 15m (upper right), 25m (lower left), and 35m (lower right) as interpolated between the 20 calculation points. Wind direction 285 degree, indicated by the arrow.

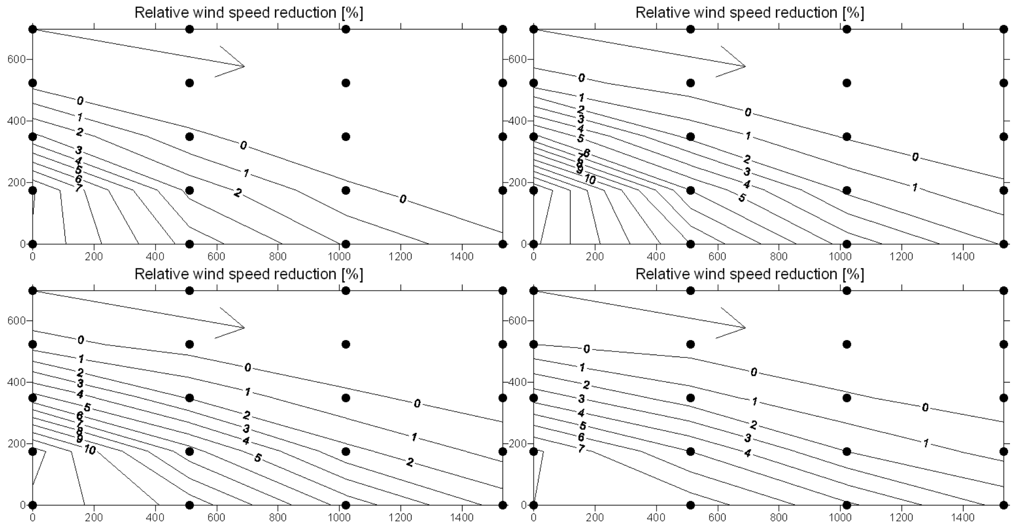

Figure 11. Wind speed reduction [%] at four heights above sea, 5m (upper left), 15m (upper right), 25m (lower left), and 35m (lower right) as interpolated between the 20 calculation points. Wind direction 300 degree, indicated by the arrow.

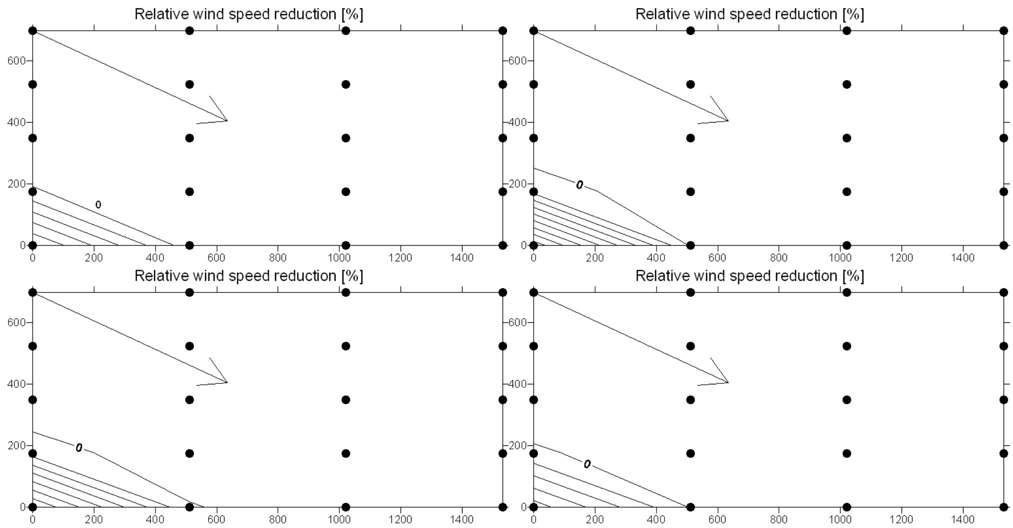

Figure 12. Wind speed reduction [%] at four heights above sea, 5m (upper left), 15m (upper right), 25m (lower left), and 35m (lower right) as interpolated between the 20 calculation points. Wind direction 315 degree, indicated by the arrow.

4 Wake effects

4.1 Generel information about wake effects

The energy conversion process by a wind turbine is basically caused by a reduction of the air flow momentum. Basically, the wind causes forces on the rotating turbine, which in contrast applies a counter pressure on the incoming flow. This counter pressure causes some of the air to pass around the turbine and some of if will pass through the rotor. Consequently there is a reduced wind speed in the area behind the wind turbine rotor. A wind turbine is (roughly speaking) designed to reduce the windspeed with 2/3 in the area immediately behind the rotor. This reduction in wind speed of 2/3 is kept constant until rated wind speed, which is normally around 12-13m/s (at hub height). For higher wind speeds, the turbine is controlled to operate at a constant power level, normally by changing the blade pitch angles. The wind speed reduction drops rapidly for increasing wind speeds since only a very small part of the energy content need to be converted in this region. For wind speeds higher than cut-out at 25m/s the turbine is fully stopped and the flow impact is negligible. The wind speed region of highest wind speed reduction is from 5-10m/s and above 16m/s (at hub height) the impact is expected to be minimal.

The flow field behind an operating rotor is quite complex, first there is the reduced wind speed area, which gradually recovers further downstream. Here it is important to notice that this region of reduced wind speed does not necessarily follow a straight line downstream of the rotor center, but depends heavily on the structure of the ambient athmospheric turbulence. In a very popular way, it can be said that the deficit is transported in the direction of the wind, but the wind direction is continuously changing due to the turbulence, see Figure 14. The movement both occurs in the horizontal as well as the vertical plane. Further on, there is the self generated vortex system from the rotor itself consisting manly of three tipvortexes and a root vortex, see illustration in Figure 13, which is transported dowstream together with the deficit. These vortices tend to dissolve a few rotor diameters downstream under normal ambient turbulent conditions. The impact further downstream is mainly a slightly increased amount of high frequent turbulence compared to normal ambient turbulence.

In general the wake effect will decrease faster under high ambient turbulence conditions and vice versa for low ambient turbulence. This study is performed for a turbulence level measured as a turbulence intensity (standard deviation / mean wind speed) of 6% corresponding to average offshore conditions.

4.2 The Dynamic Wake Meander model

The Dynamic Wake Meandering (DWM) model complex is based on the combination of three corner stones; 1) modeling of quasi-steady wake deficits, (Madsen et al., 2010); 2) a stochastic model of the down wind wake meandering; and 3) added -or self generated wake turbulence. The wake meandering part is based on a fundamental presumption stating that the transport of wakes in the atmospheric boundary layer can be modeled by considering the wakes to act as passive tracers driven by the large-scale turbulence structures in lateral and vertical directions, (Larsen et al., 2008a). Modeling of the meandering process consequently includes considerations of a suitable description of the “carrier” stochastic transport media as well as of a suitable definition of the cut-off frequency defining large-scale turbulence structures in this context. For the stochastic modeling of wake meandering, we imagine the wake as constituted by a cascade of wake deficits, each “emitted” at consecutive time instants in agreement with the passive tracer analogy (Larsen et al., 2008a), (Larsen et al., 2007). We then subsequently describe the propagation of each of the emitted wake deficits, and the collective description of these thus constitutes the wake meandering model. Adopting Taylor’s hypothesis (Taylor, 1937), the

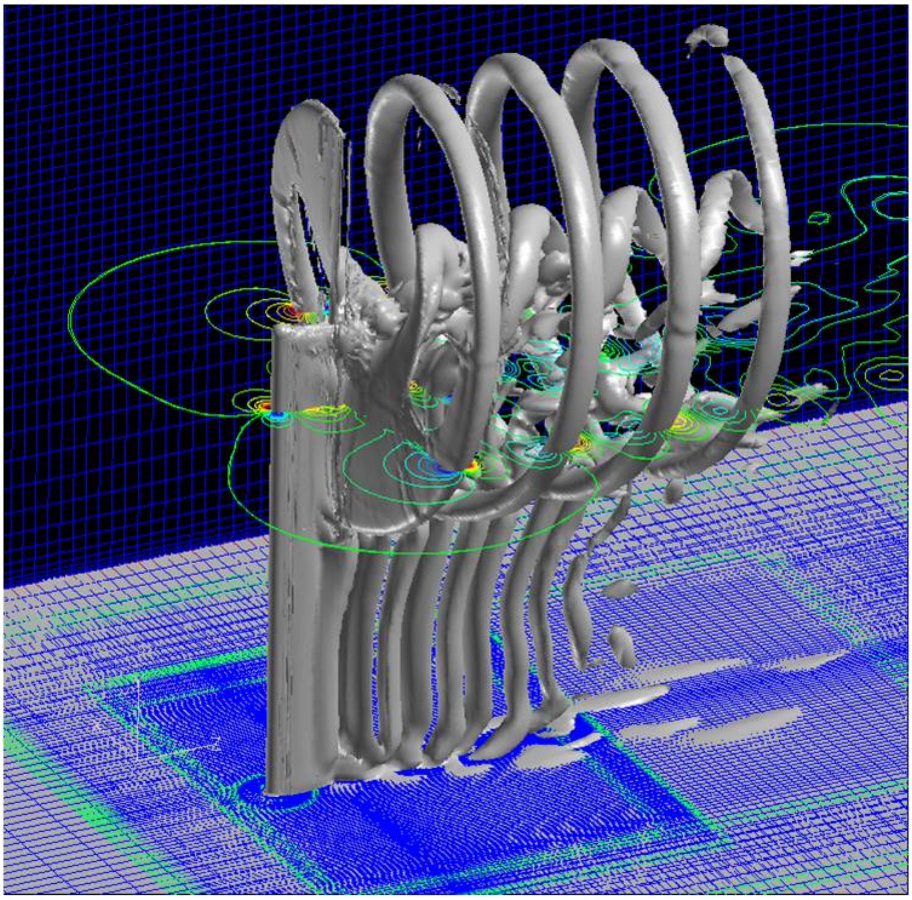

Figure 13. Illustration of the complicated vortex system in the near wake region of a wind turbine. This example is from a down wind configured wind turbine operating in non-turbulent inflow. Courtesy F. Zahle, DTU Wind Energy 2010.

down-stream advection of these is assumed to be controlled by the mean wind speed of the ambient wind field. With this formulation the wake momentum in the direction of the mean flow is invariant with respect to down stream displacement. This is a considerable simplification allowing for a straight forward decoupling of the wake along wind deficit profile (and its expansion) and the wake transportation process. As for the dynamics in the lateral- and vertical directions, each considered wake cascade-element is displaced according to the large-scale lateral- and vertical turbulence velocities at the position of the particular wake cascade element at each time instant. The choice of a suitable stochastic turbulence field, that in turn defines the stochastic wake transport process, is not mandatory, but may be guided by the characteristics of the atmospheric turbulence at the site of relevance. These characteristics encompass in principle not only turbulence standard parameters such as turbulence intensity, turbulence length scale and coherence properties, but also features like degree of isotropy and homogenity of the turbulence, Gaussianity of the turbulence etc. The meandering mechanism in the DWM model was initially verified for small turbine distances by pitot tube measurements on a NEG Micon NM80 turbine, (Thomsen and Madsen, 2005) and later verified by correlating DWM predictions with direct full-scale measurements of the instantaneous wake position obtained from LiDAR recordings, (Bingöl et al., 2010).

In the present implementation, the DWM model is fully integrated in the HAWC2 framework as a supplement to the wind module. Details can be found in (Madsen et al., 2010). The additional input to the traditional aerodynamic inputs of the aeroelastic code consist simply of positions of neighboring wind turbines and turbulence properties for the ambient turbulence.

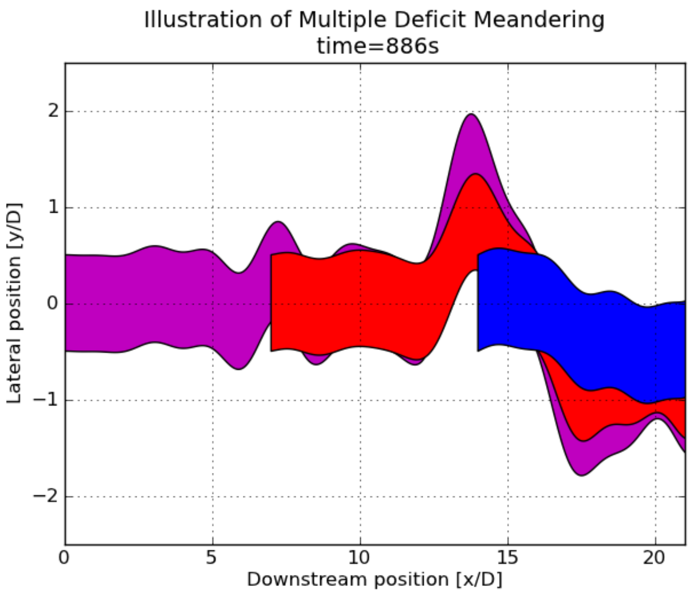

Figure 14. Illustration of the meandering path of multiple turbine wakes.

4.3 Wake impact study

Using the Dynamic wake meander model, the wind condition in the surf area is quantified based on mean wind speed and turbulence level. Three configurations analyzed are:

1. Existing 4 DANmark 525kW turbines
2. New planned 10 wind turbines with a nominal power of 3MW and a rotor diameter of 112m, top height of 150m.

All configurations are investigated for the exact same ambient turbulence field, generated based on a assumed turbulence intensity of 6% corresponding to normal offshore conditions. Effects from buildings etc. at shore is completely ignored. It is also assumed that the wind speed gradient follows a power low profile with an exponent of $\alpha = 0.12$, see (1) and Figure 15.

$$U(z) = U_0(\frac{z}{z_0})^{\alpha} \tag{1}$$

The situations covered are wind speeds at 8,10,12,14,16m/s for the wind directions 270, 285, 300 and 315°. Examples of time simulations are shown in Figure 18 and 29, whereas the surface plots of all simulated conditions with respect to mean wind speed, wind direction as well as turbulence level extracted at 10m height are shown in the Figures 30 to 49.

In general the impact of wind turbine wake is very limited in the eastern part of the surf area, whereas a reduction in mean wind speed in combination with increased turbulence intensity is seen in the western area. The worst case scenario is seen at 8m/s with wind direction from 285°. In Figure 18 the impact at position 2 (western part of surf area) can be seen. The wakes are seen to occasionally cause regions of reduced wind speed. This is seen for all extracted heights between 5 and 20m. A slightly lower impact at 5m than 20m height is also seen. For the same situation, but extracted at an eastern location at position 17, a considerable lower impact is seen. For this location, it is mainly a reduced mean wind speed and the influence for surfers is expected minimal.

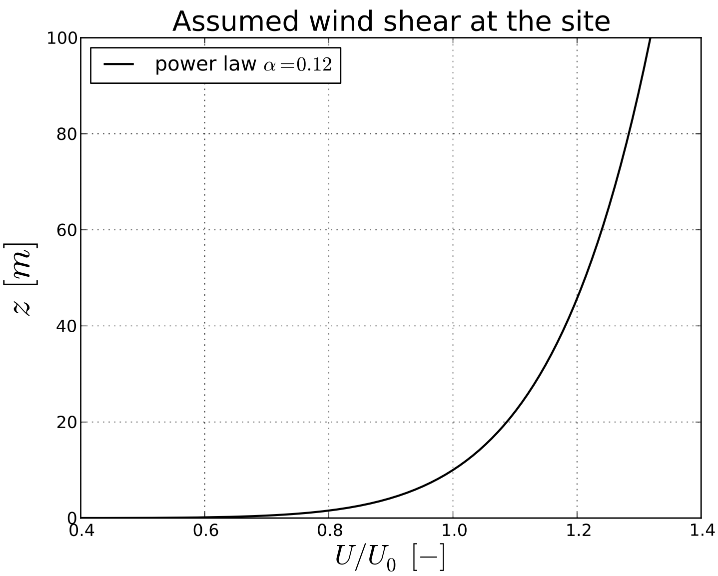

Figure 15. Shear profile used in the wake studies.

For the same wind speed of 8m/s, but now with a wind direction of 315°, timeseries are shown for pos 2 and 17 in Figure 20 and 21. No wake effects are seen.

The same type of extracted time series have been shown for 12m/s (Figure 22, 23,24, 25) and 16m/s (Figure 26, 27,28, 29). In general smaller influence is seen for increasing wind speed, which is caused by a relatively lower power extraction from the upstream wind turbines. At the wind direction of 285° (which is the worst direction) there is still an increased turbulence level at 12m/s in the western location, whereas at 16m/s the disturbances are minimal. At wind direction of 315° no impact can be seen for any wind speed.

In order to provide an overview of the consequence for the entire surf area, surface plots have been shown in Figure 30 to 49. In these plots, changes in mean wind speed as well as turbulence level are illustrated between existing and expected new conditions. The turbulence level is shown both measured as a standard deviation and as a turbulence intensity. In the original conditions, a turbulence intensity of 6% have been assumed corresponding to offshore conditions. The plot showing standard deviation illustrate the deviations with units in m/s. This corresponds to the absolute change in wind speed seen from a surfer. The turbulence intensity is the standard deviation normalized by the local mean wind speed, which is the normal way to illustrate mechanically generated turbulence. The colors in the plots have been chosen so red (worst) represents a reduction of 50% for the mean wind speed, and a doubled turbulence level for the standard deviation and intensity plots.

4.4 How to combine turbulence from sheltering with turbine wakes

The question how to combined turbulence from background turbulence, shelter effects and wake effects is not straight forward. A conservative approach is to superimposed the standard deviation from shelter with background and wake (which is allready combined). The philosophy of this is that the turbulence generated by the shelter adds to the background turbulence, which again has an impact on the wake mechanism (mixing and meandering). In order to investigate how the combined effect of shelter and wind turbine wakes would be, a few wake simulations with an increased ambient turbulence intensity of 12% was carried out (conservative combination of 6% ambient and 6% from sheltering). It can be seen in Table 1 that if the ambient turbulence increase by 6%, the final turbulence intensity including wakes is also increased by 6%.

However, the building are located inside the wind turbine area and the turbulence generated is not necessarily the same as fully developed ambient turbulence. The vortices from the sheltering starts from the near surface and gradually rises. The impact on the meandering of turbine wake is most likely. Further on, these vortices generated by sheltering are statistically independent of the instantaneous background vortices, meaning that the combination should be a summation of velocity variation in time domain. The effect of this has been investigated by adding the contributions from sheltering and wakes as times series. Basically this is a linear combination of time series from the wind turbine study together with time series of natural turbulence intensity. The assumption is that turbulence vortex structures generated from buildings are statistically independent of the vortex structures from the background turbulence and the turbines. It is assumed that the building generated turbulence has same length scale as the ambient background turbulence, but being statistically independent (hence generated with a different seed factor). Some times the turbulence velocity will result in larger variation whereas cancellation will occur at other times. An example of this is shown in Figure 16 and 17. The final standard deviation is significantly lower than by adding the standard deviation together directly and a square root summation, shown in equation 2 seem better.

$$\sigma_{total} = \sqrt{\sigma^2_{shelter} + \sigma^2_{wake+background}} \tag{2}$$

Table 1. Influence on added backgrund turbulence for wind turbine wake effects

Case	U	σ	TI
U=8, TI=0.06, pos 2	7.41	0.688	0.093
U=8, TI=0.12, pos 2	7.35	1.155	0.155
U=8, TI=0.06, pos 17	7.55	0.558	0.77
U=8, TI=0.12, pos 17	7.62	0.979	0.129

4.5 Conclusion on wake effects

Wake effects are clearly seen at 10m/s and below for wind directions between 270 and 300°, with biggest influence in the western part of the surf area. Wind speed reduction are in general below 10%, whereas the turbulence in the worst case increase with 50%. Only minor impact is seen in the eastern part of the area or in general for wind speeds above 12m/s.

In order to investigate how the combined effect of shelter and wind turbine wakes would be time simulations of turbine wake and building generated turbulence was added in time domain. If the ambient turbulence is increase by 6% (due to the shelter induced turbulence level) and the turbulence from the turbines also increase by 6%, the final turbulence intensity is increased by 8%, hence the turbulence levels should be added together as a square root summation.

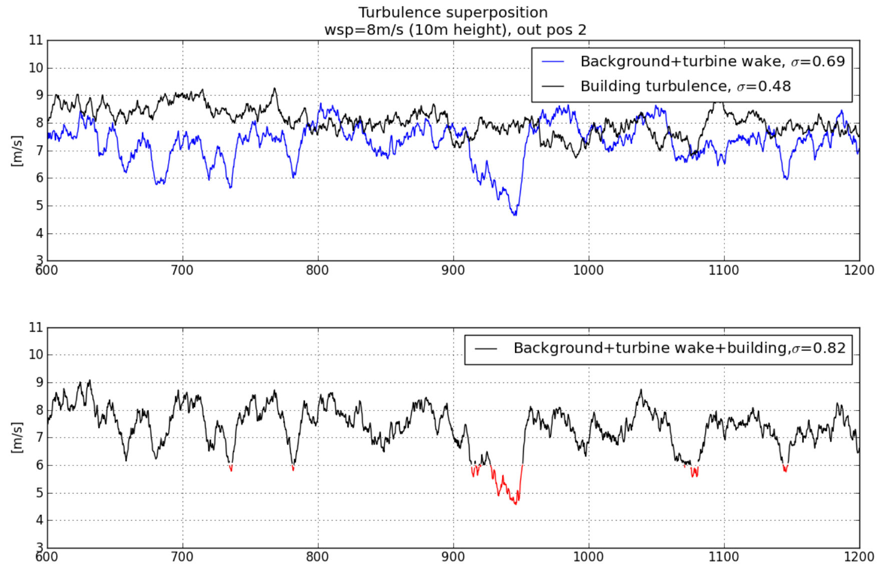

Figure 16. Example of superposition of turbulence. This can be used for analysis in time domain of number of period wind speed dropping below a certain value, which is shown in the lowest figure using a threshold limit of 2m/s below the mean of the ambient wind speed of 8m/s. This case corresponds to the wake simulation shown in Figure 18 which is expected to be worst case scenario.

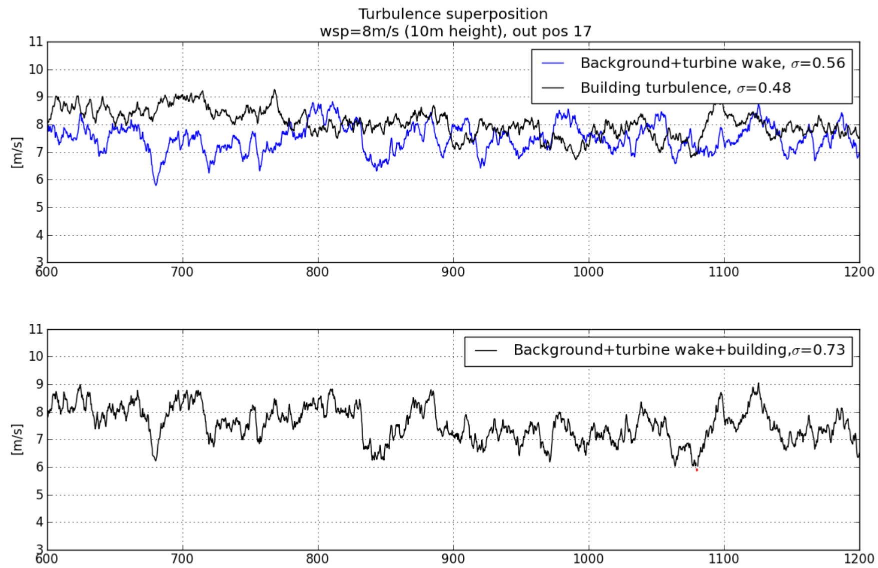

Figure 17. Example of superposition of turbulence. This can be used for analysis in time domain of number of period wind speed dropping below a certain value, which is shown in the lowest figure using a threshold limit of 2m/s below the mean of the ambient wind speed of 8m/s. This case corresponds to the wake simulation shown in Figure 19.

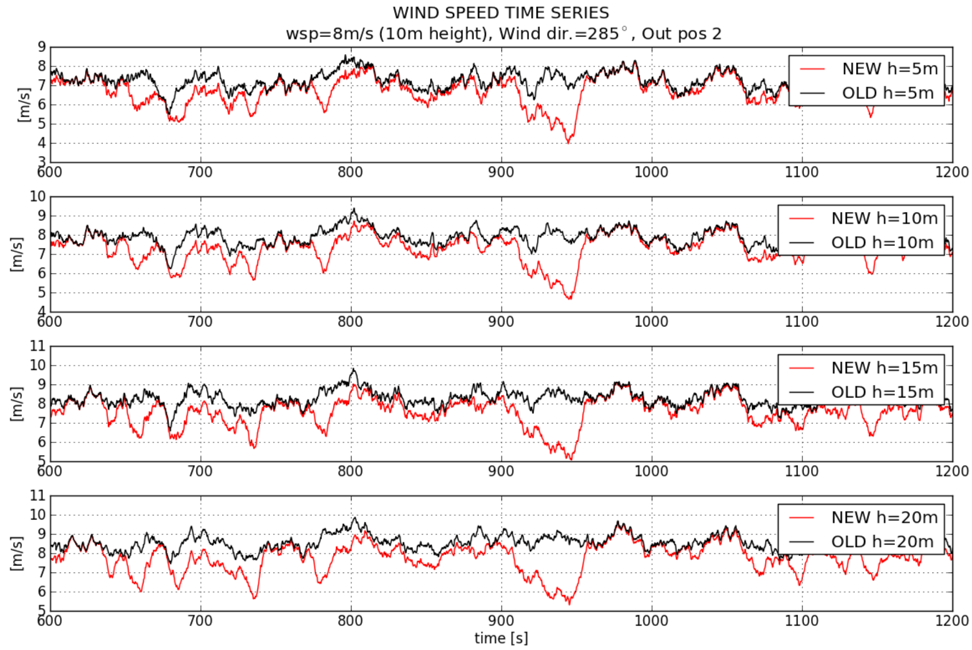

Figure 18. Time series of wake effect at out pos 2, with clearly visible wake effects representing the worst case scenario. The wind speed is 8m/s at 10m height, wind direction 285°.

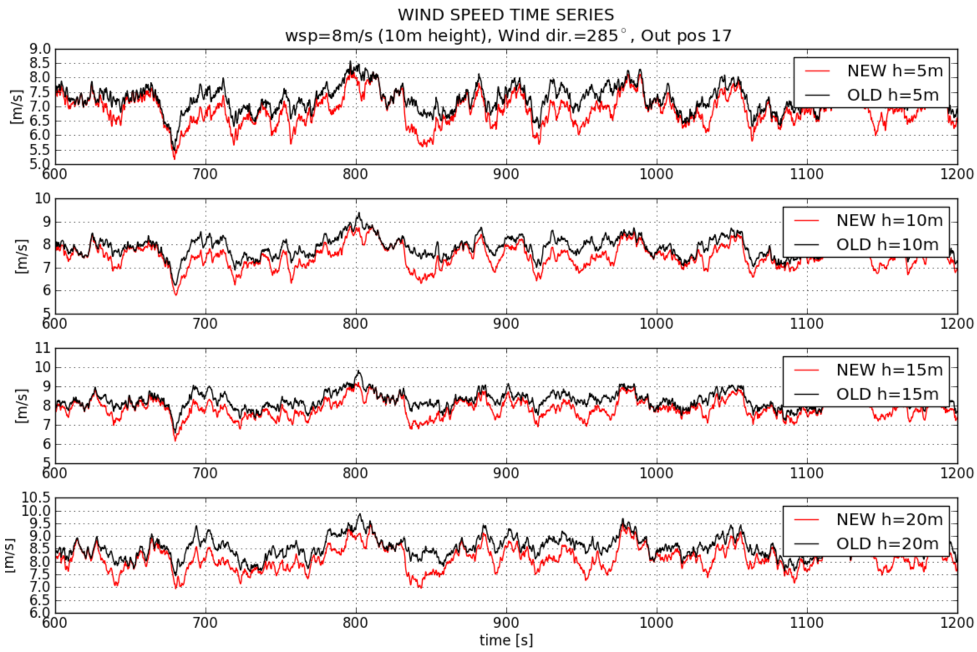

Figure 19. Time series of wake effect at out pos 17. The wind speed is 8m/s at 10m height, wind direction 285°.

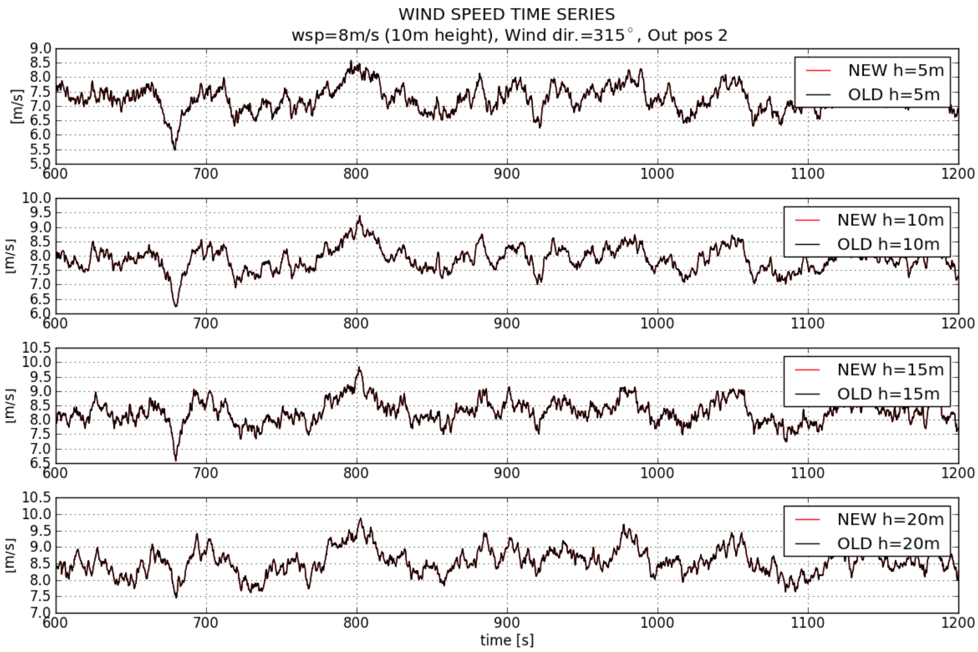

Figure 20. Time series of wake effect at out pos 2. The wind speed is 8m/s at 10m height, wind direction 315°.

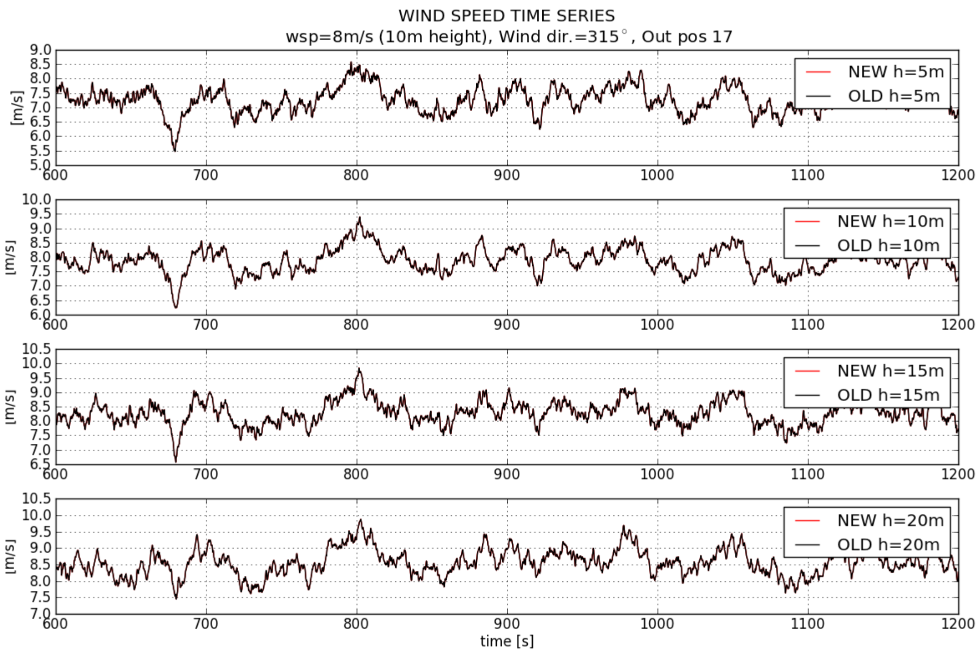

Figure 21. Time series of wake effect at out pos 17. The wind speed is 8m/s at 10m height, wind direction 315°.

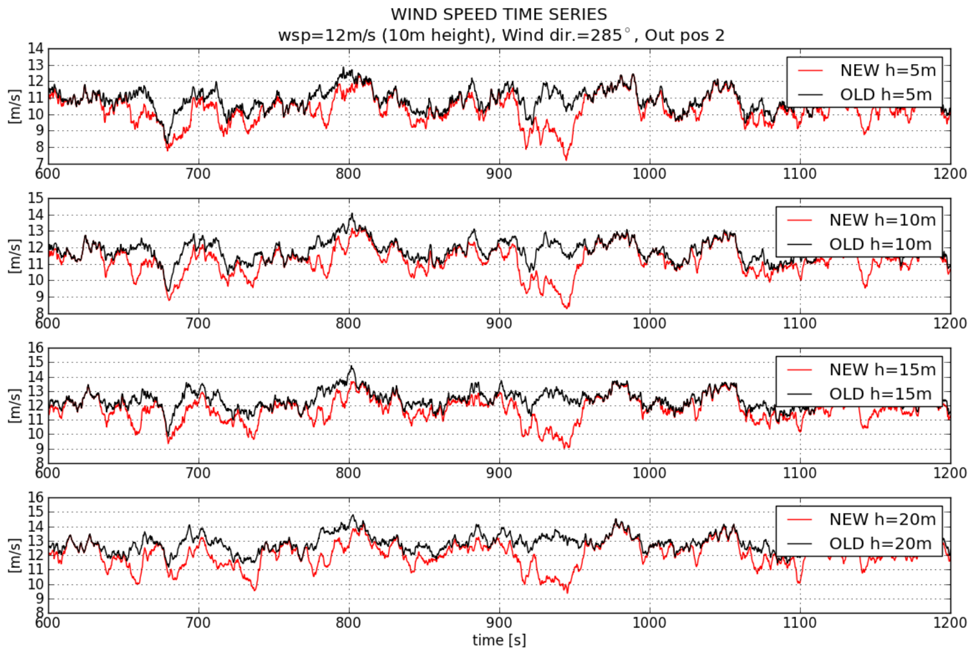

Figure 22. Time series of wake effect at out pos 2. The wind speed is 12m/s at 10m height, wind direction 285°.

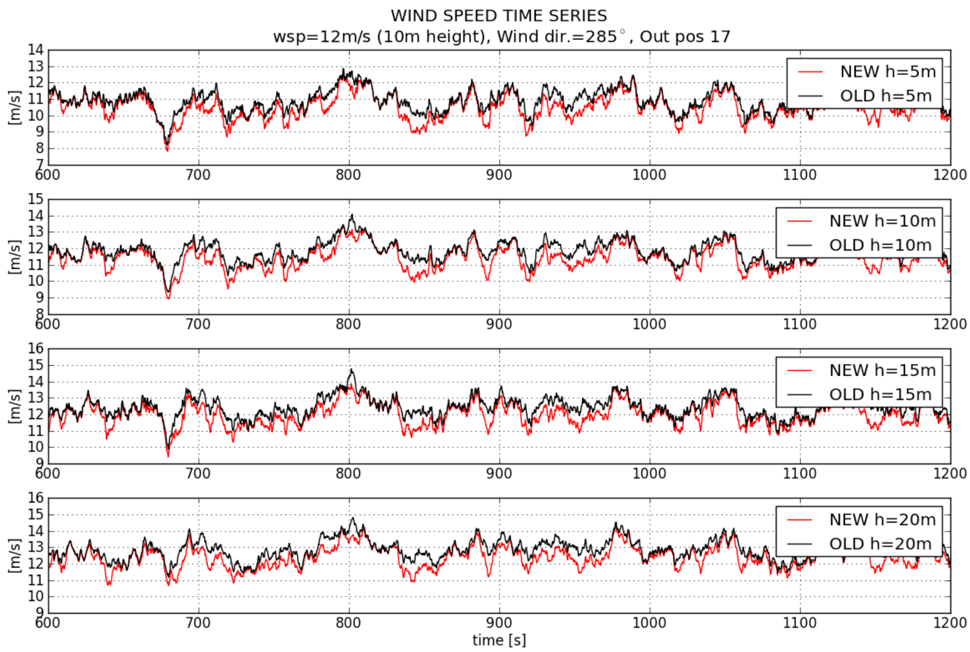

Figure 23. Time series of wake effect at out pos 17. The wind speed is 12m/s at 10m height, wind direction 285°.

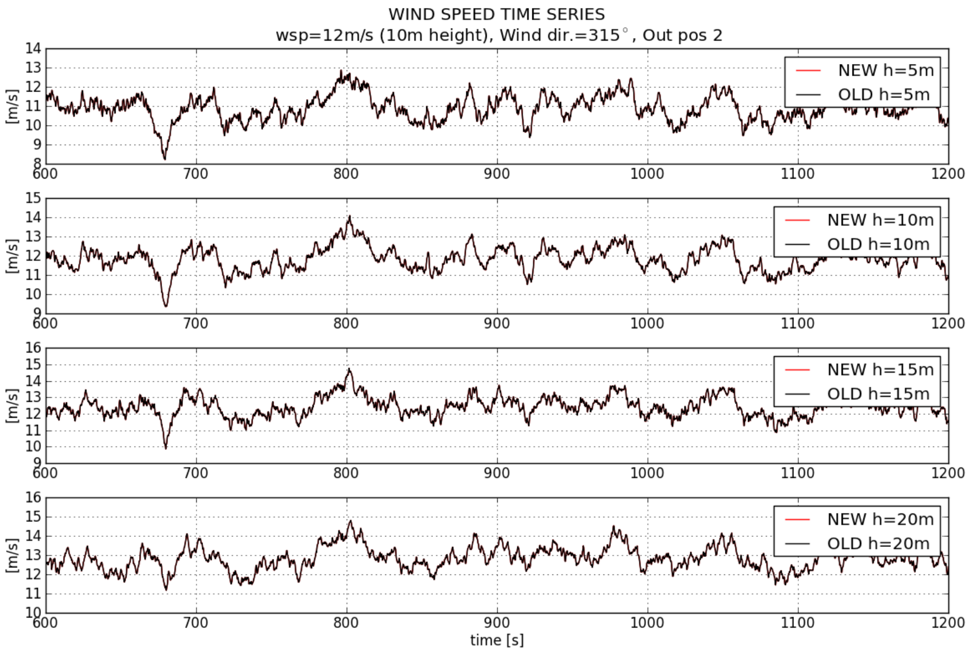

Figure 24. Time series of wake effect at out pos 2. The wind speed is 12m/s at 10m height, wind direction 315°.

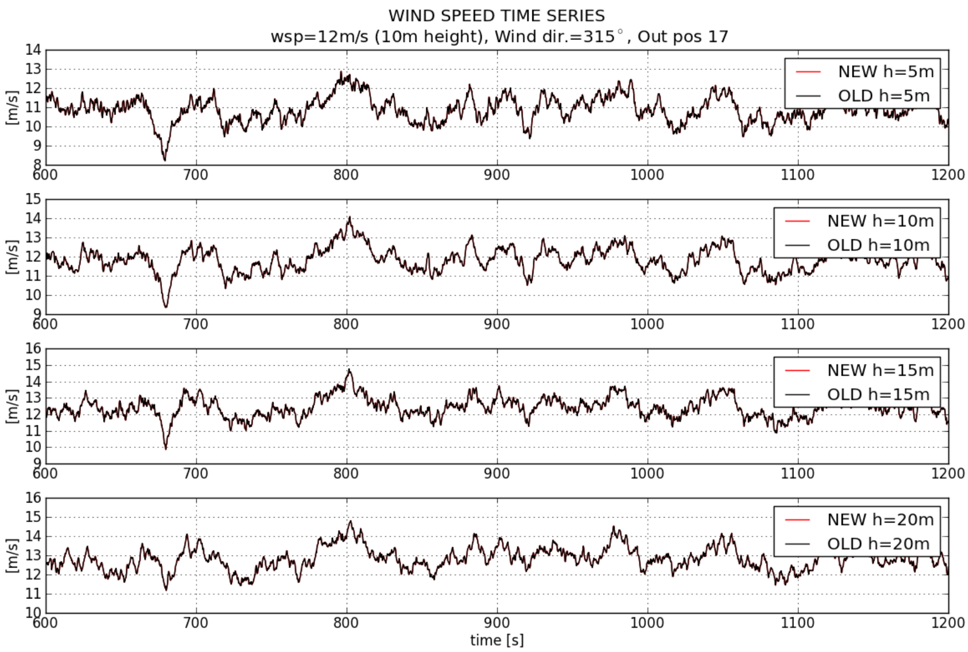

Figure 25. Time series of wake effect at out pos 17. The wind speed is 12m/s at 10m height, wind direction 315°.

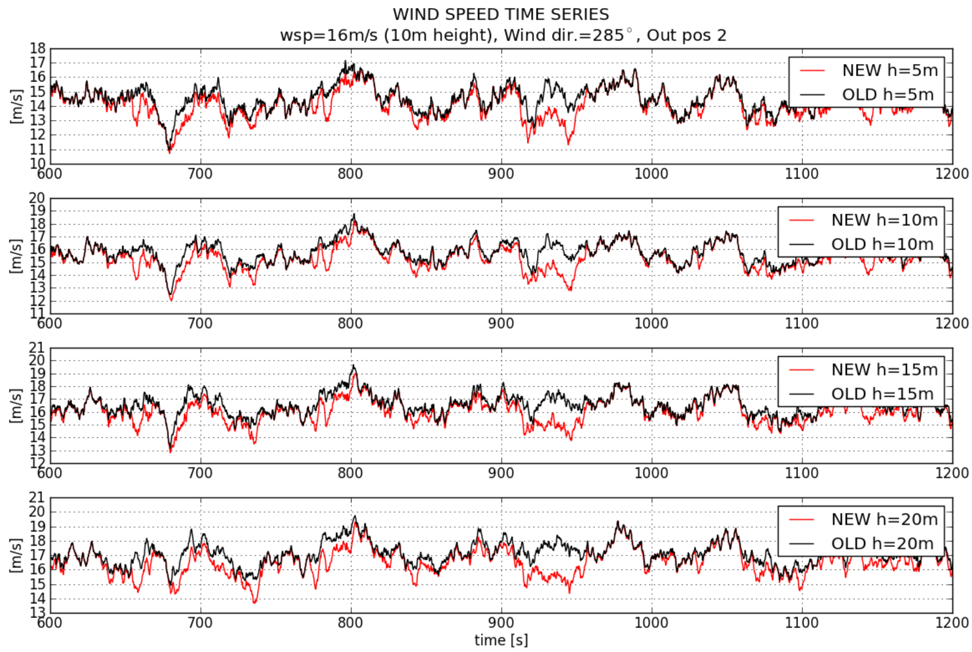

Figure 26. Time series of wake effect at out pos 2. The wind speed is 16m/s at 10m height, wind direction 285°.

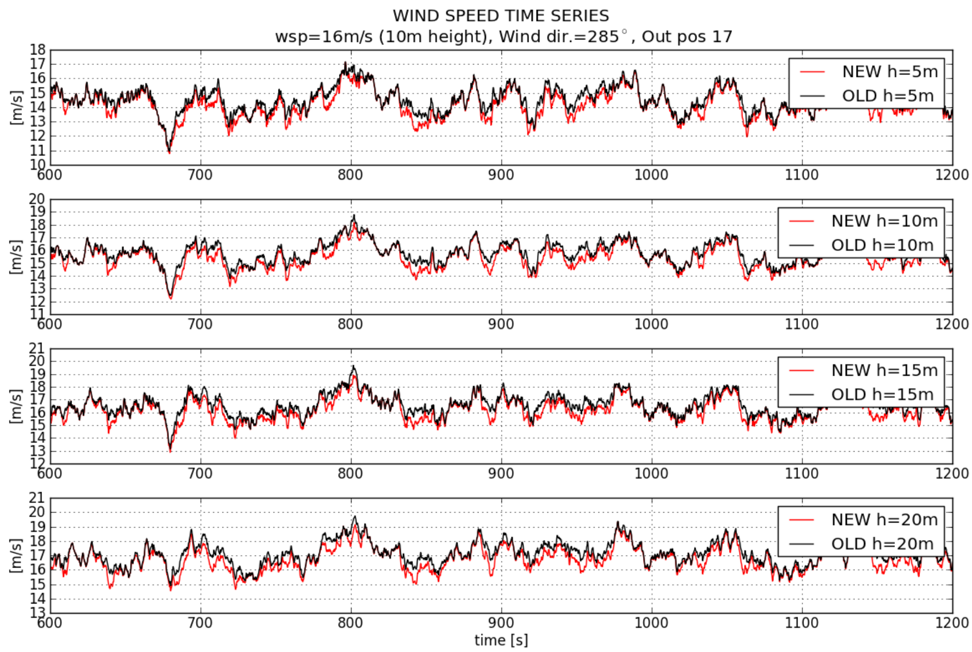

Figure 27. Time series of wake effect at out pos 17. The wind speed is 16m/s at 10m height, wind direction 285°.

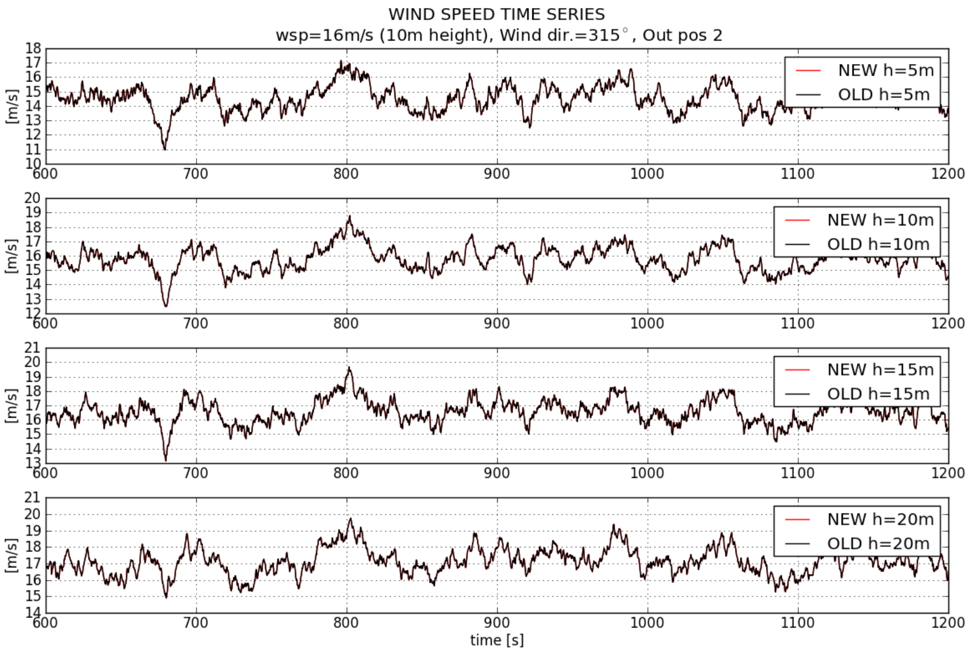

Figure 28. Time series of wake effect at out pos 2. The wind speed is 16m/s at 10m height, wind direction 315°.

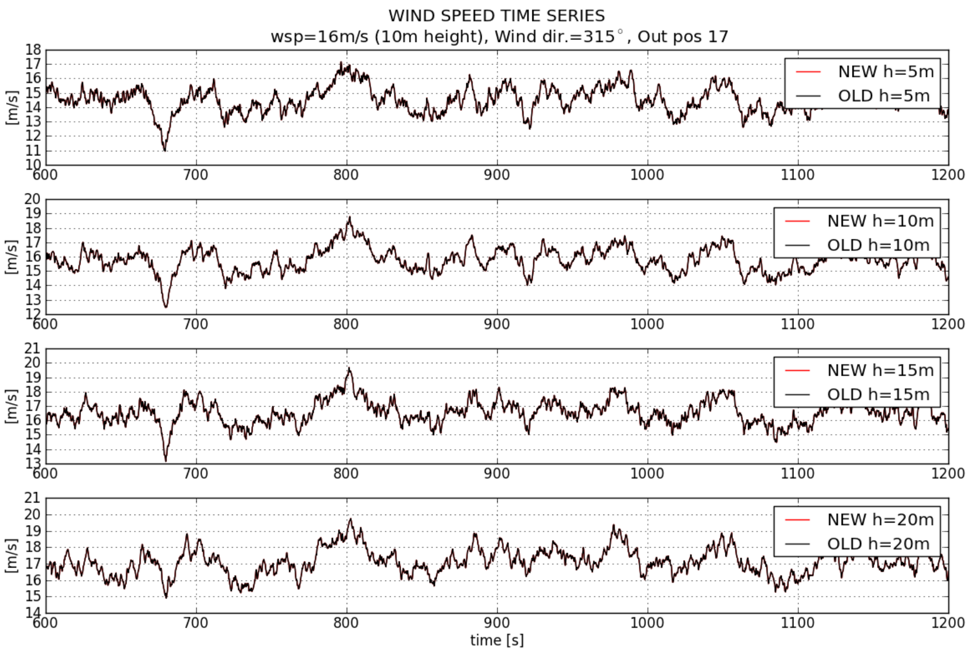

Figure 29. Time series of wake effect at out pos 17. The wind speed is 16m/s at 10m height, wind direction 315°.

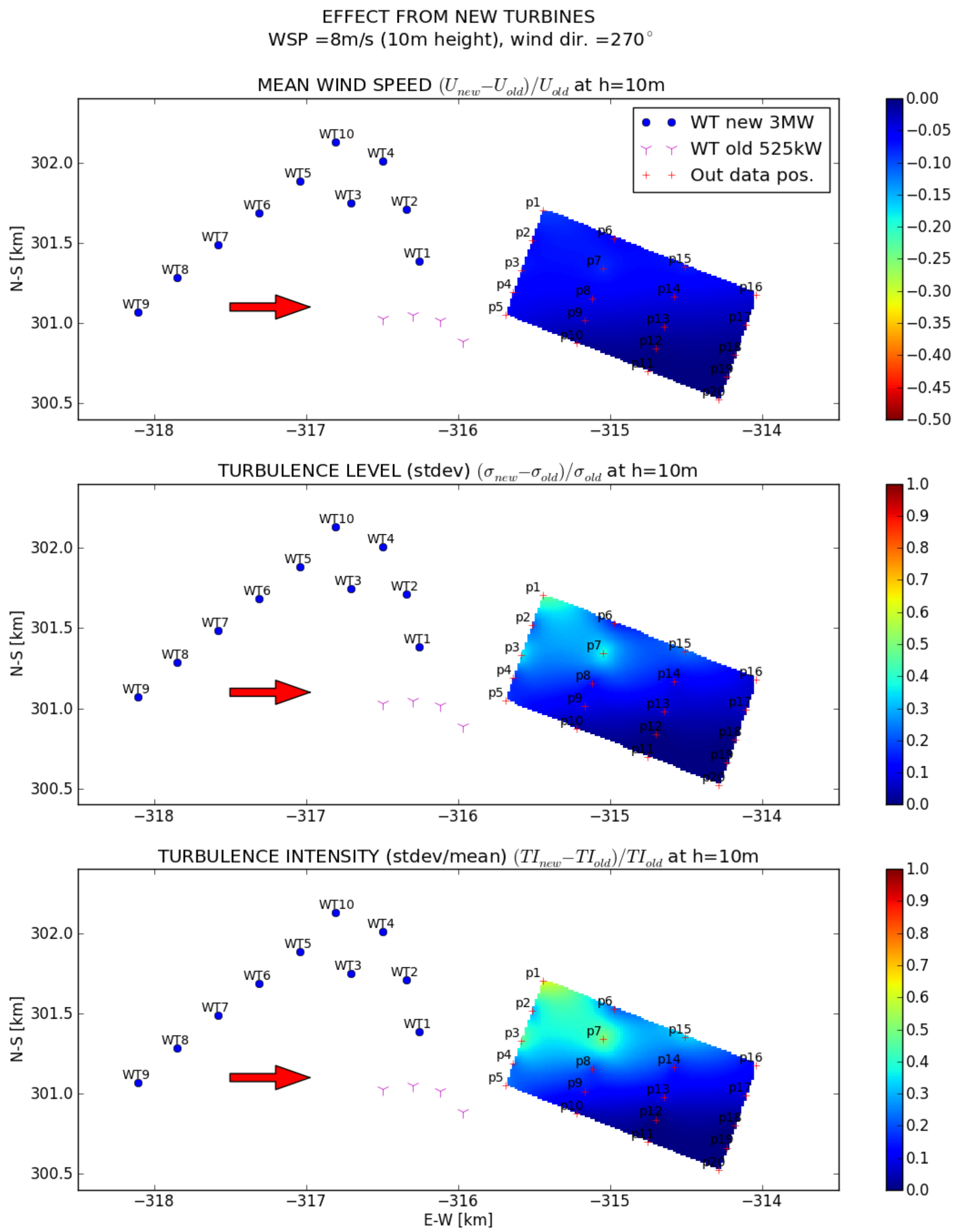

Figure 30. Wake effects from the new planned 3MW turbines relative to the existing wind conditions at 8m/s (10m height) and a wind direction of 270°. From top: relatively added mean wind speed [-], relatively added turbulence standard deviation [-], relatively added turbulence intensity [-].

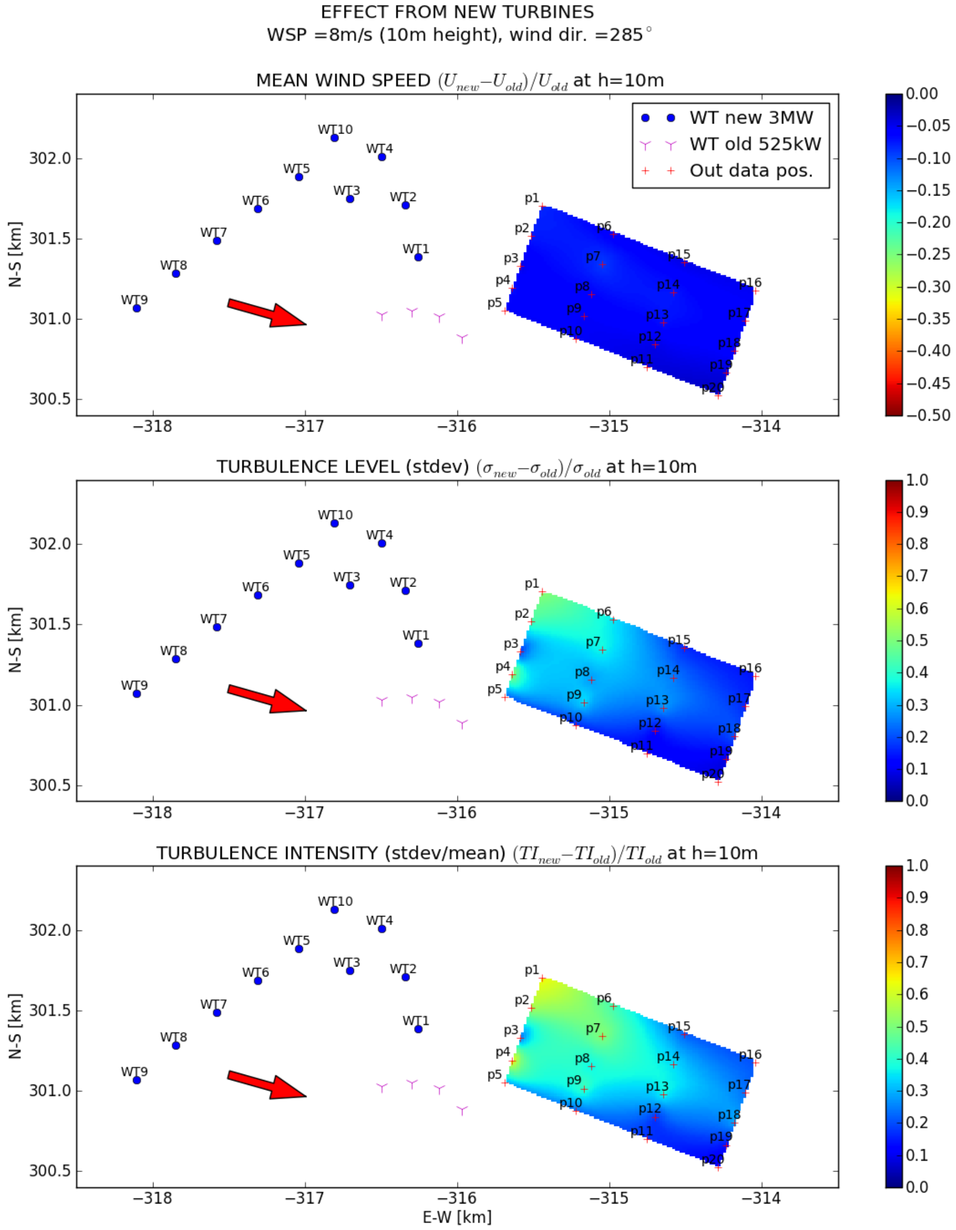

Figure 31. Wake effects from the new planned 3MW turbines relative to the existing wind conditions at 8m/s (10m height) and a wind direction of 285°. From top: relatively added mean wind speed [-], relatively added turbulence standard deviation [-], relatively added turbulence intensity [-].

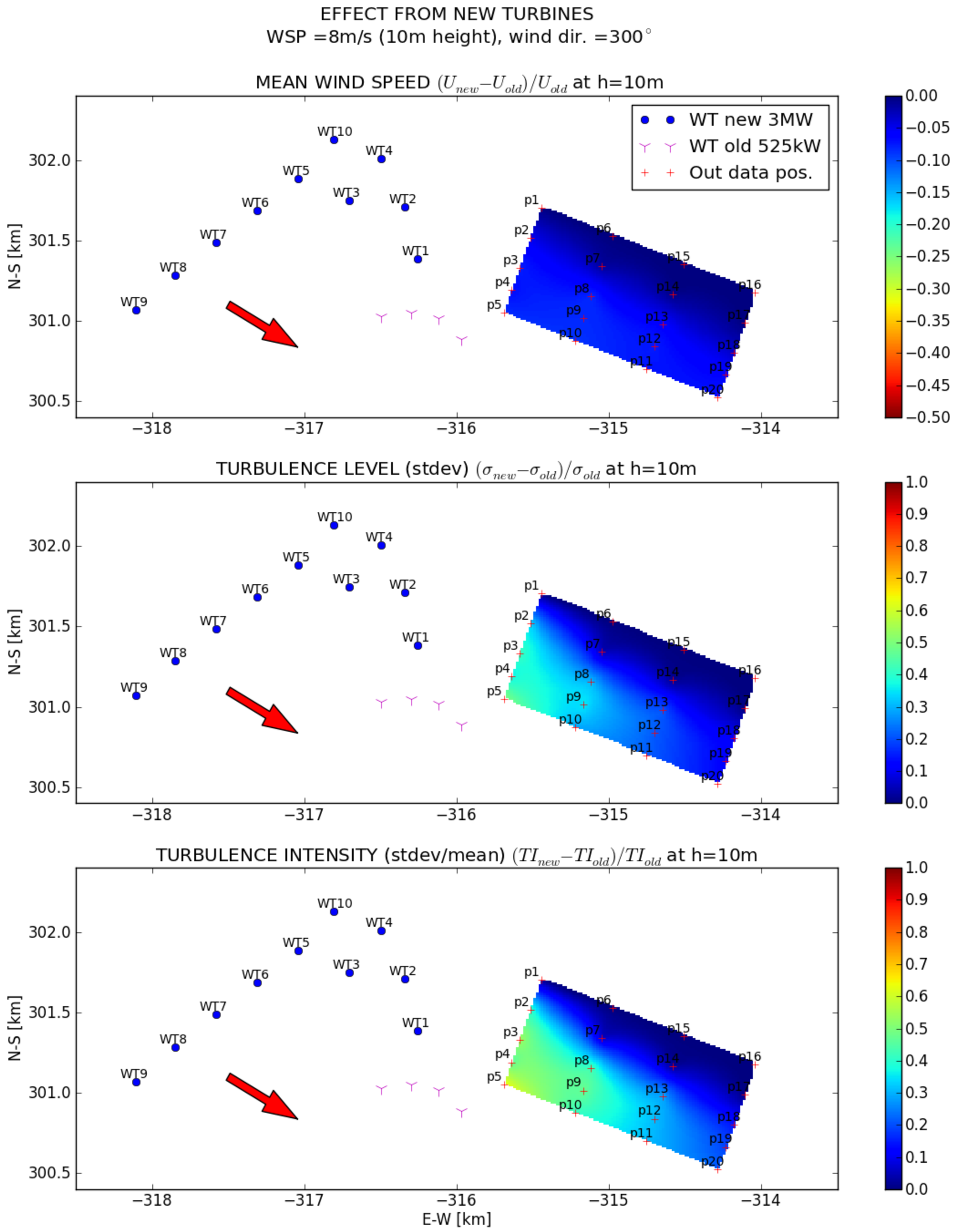

Figure 32. Wake effects from the new planned 3MW turbines relative to the existing wind conditions at 8m/s (10m height) and a wind direction of 300°. From top: relatively added mean wind speed [-], relatively added turbulence standard deviation [-], relatively added turbulence intensity [-].

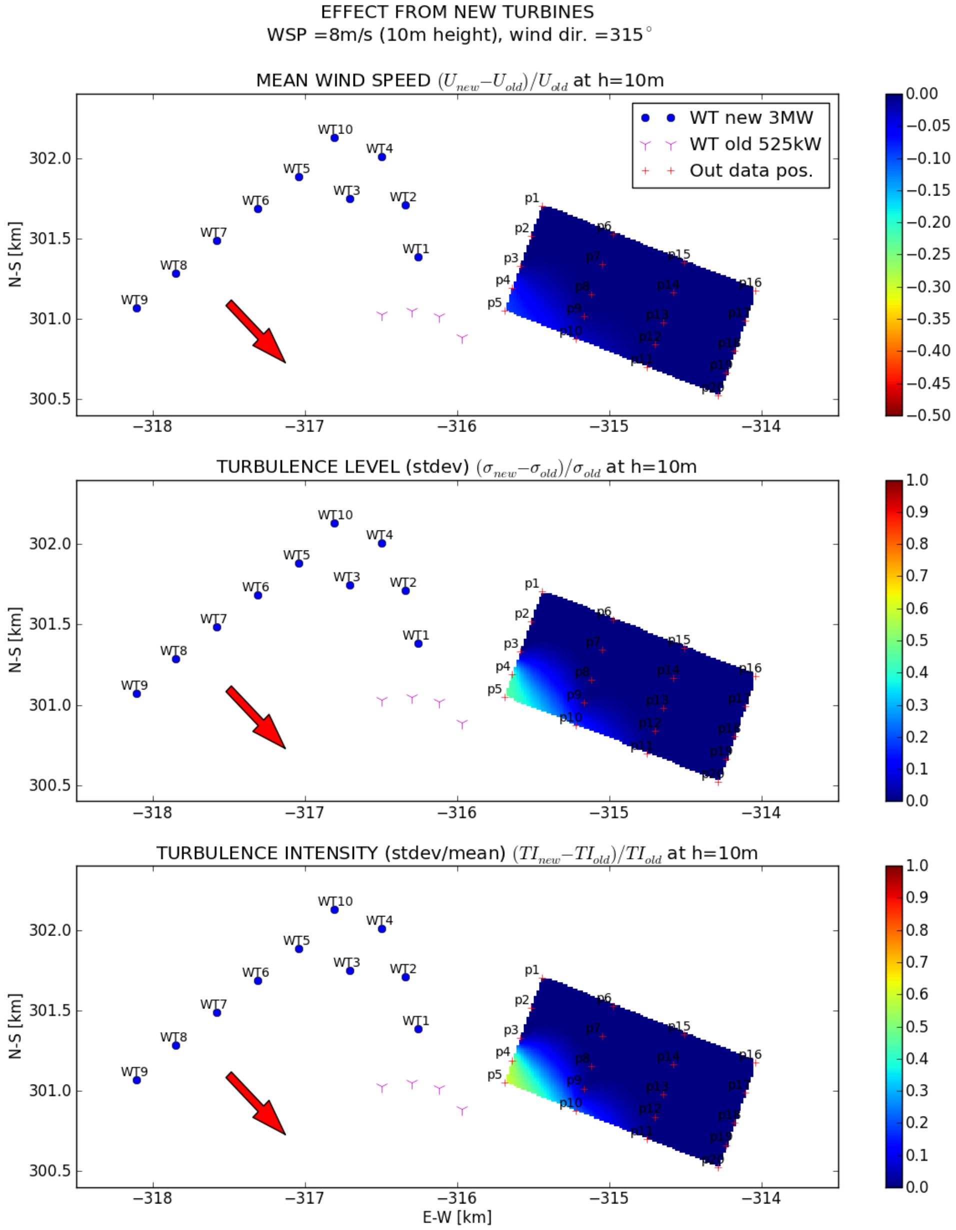

Figure 33. Wake effects from the new planned 3MW turbines relative to the existing wind conditions at 8m/s (10m height) and a wind direction of 315°. From top: relatively added mean wind speed [-], relatively added turbulence standard deviation [-], relatively added turbulence intensity [-].

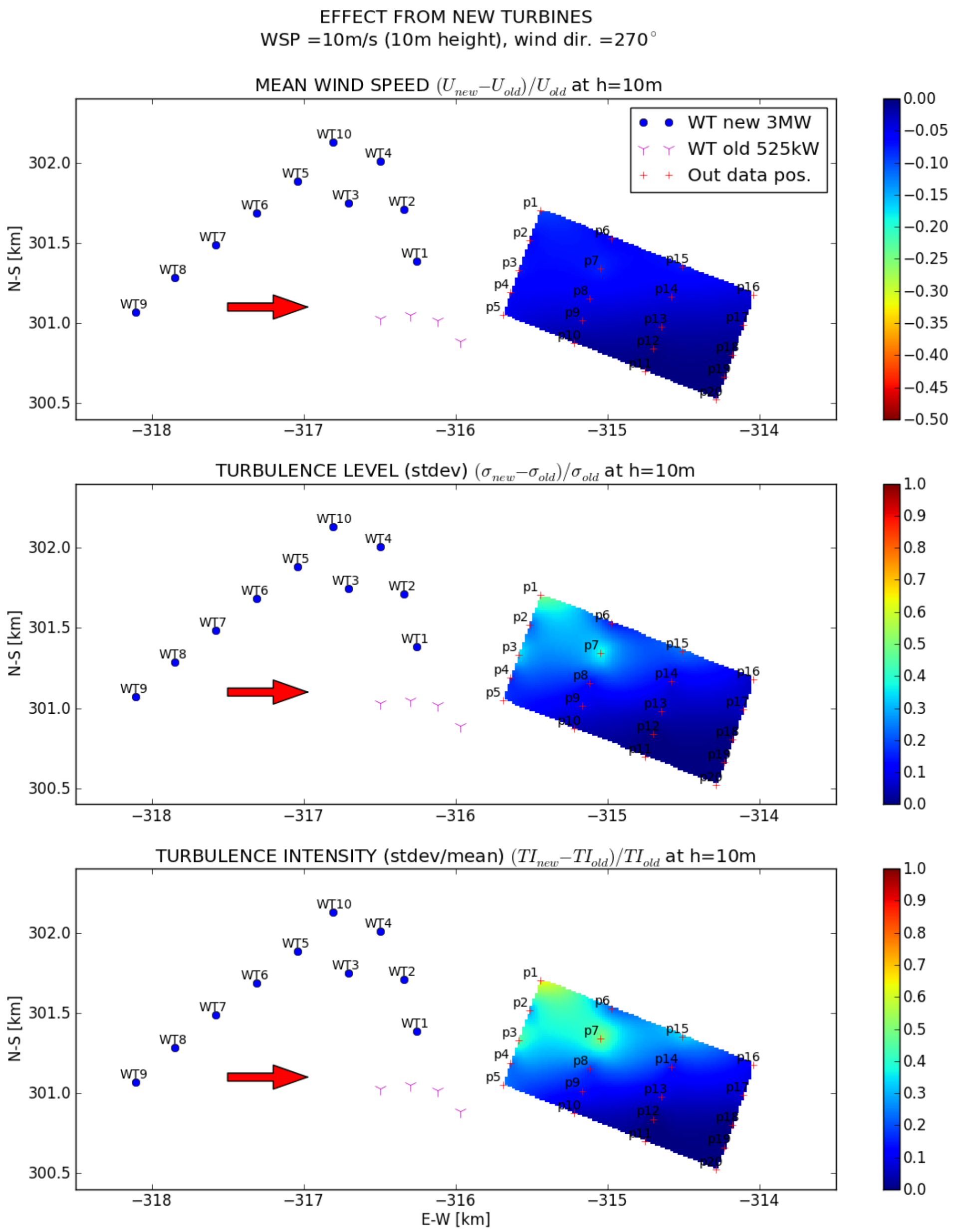

Figure 34. Wake effects from the new planned 3MW turbines relative to the existing wind conditions at 10m/s (10m height) and a wind direction of 270°. From top: relatively added mean wind speed [-], relatively added turbulence standard deviation [-], relatively added turbulence intensity [-].

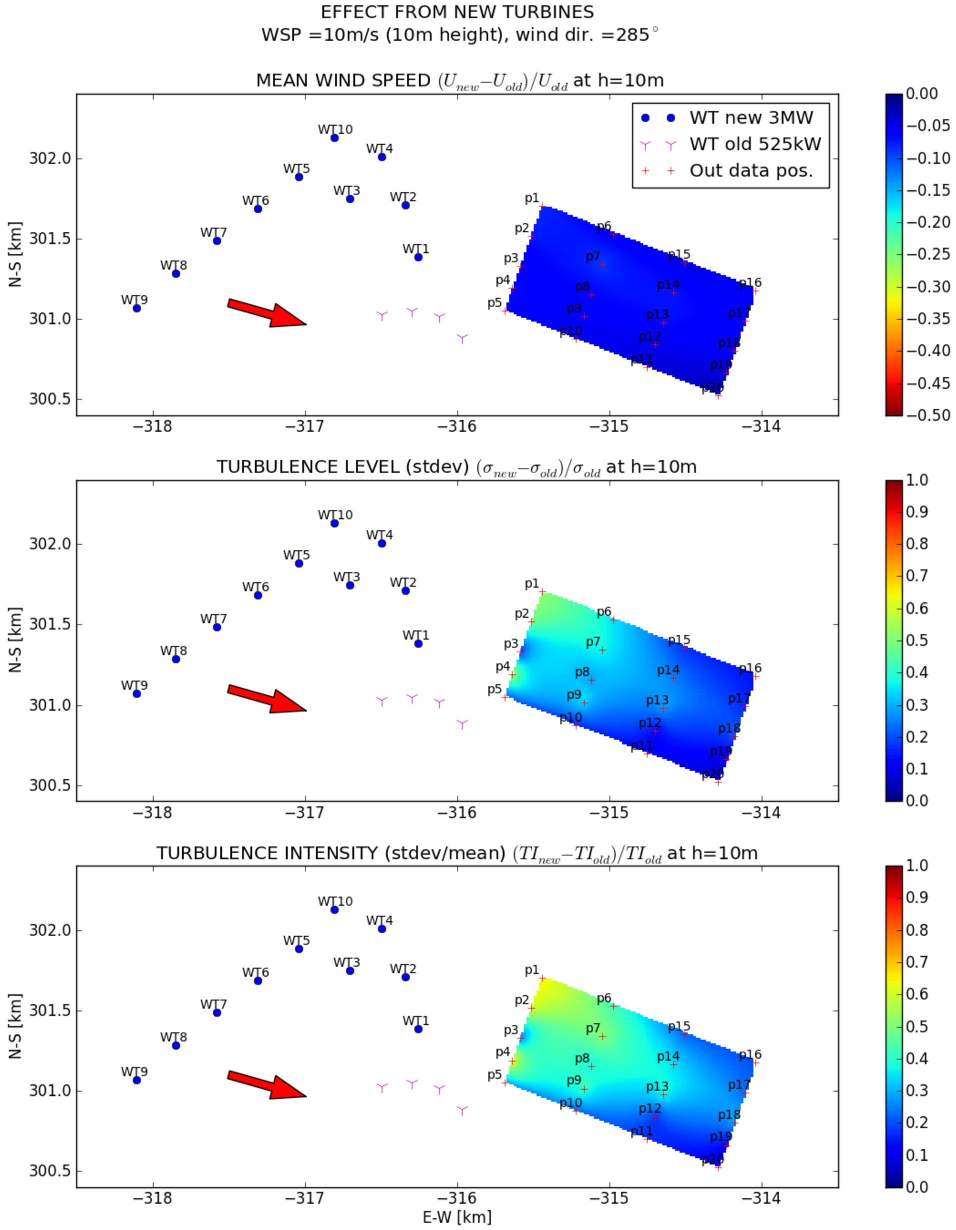

Figure 35. Wake effects from the new planned 3MW turbines relative to the existing wind conditions at 10m/s (10m height) and a wind direction of 285°. From top: relatively added mean wind speed [-], relatively added turbulence standard deviation [-], relatively added turbulence intensity [-].

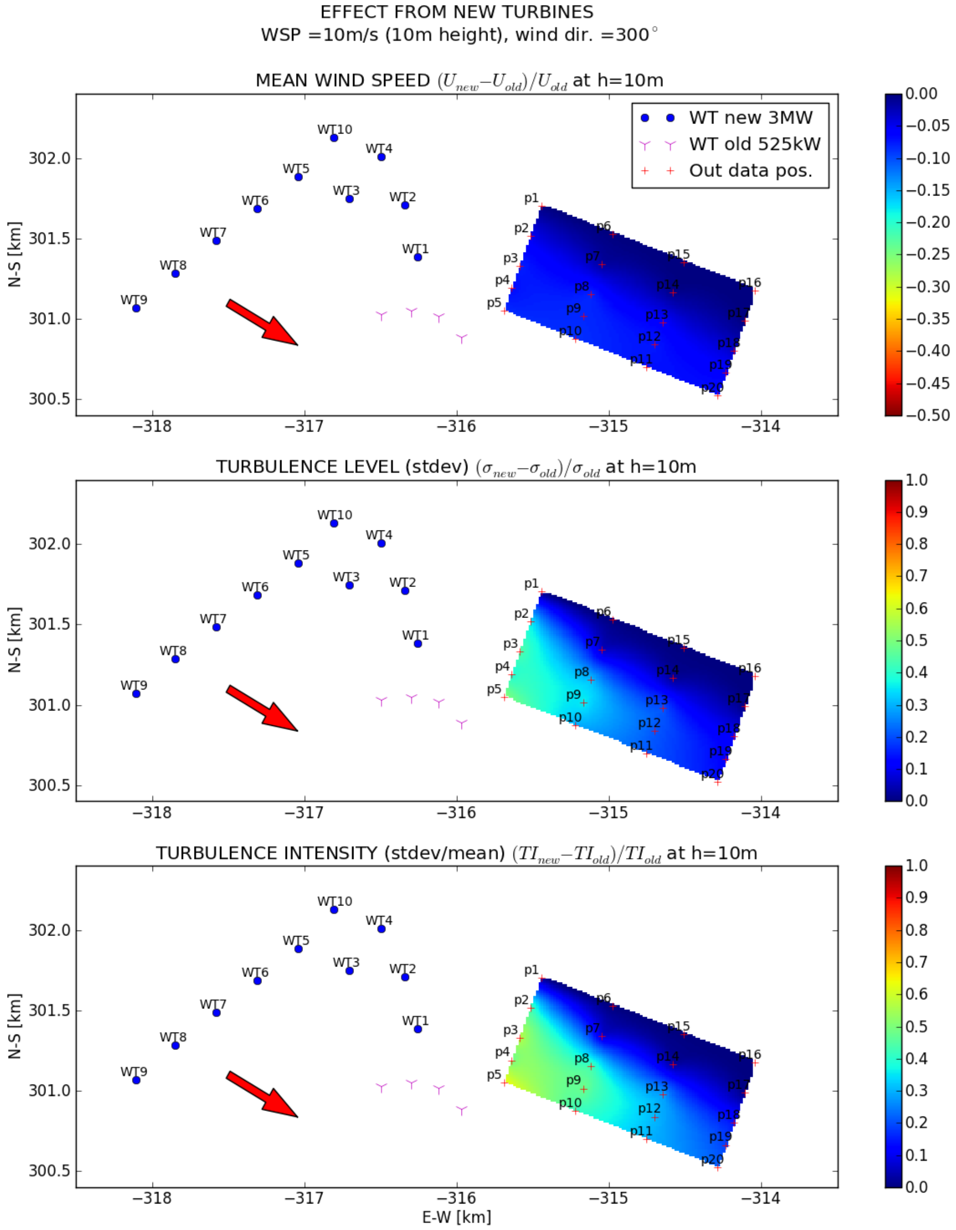

Figure 36. Wake effects from the new planned 3MW turbines relative to the existing wind conditions at 10m/s (10m height) and a wind direction of 300°. From top: relatively added mean wind speed [-], relatively added turbulence standard deviation [-], relatively added turbulence intensity [-].

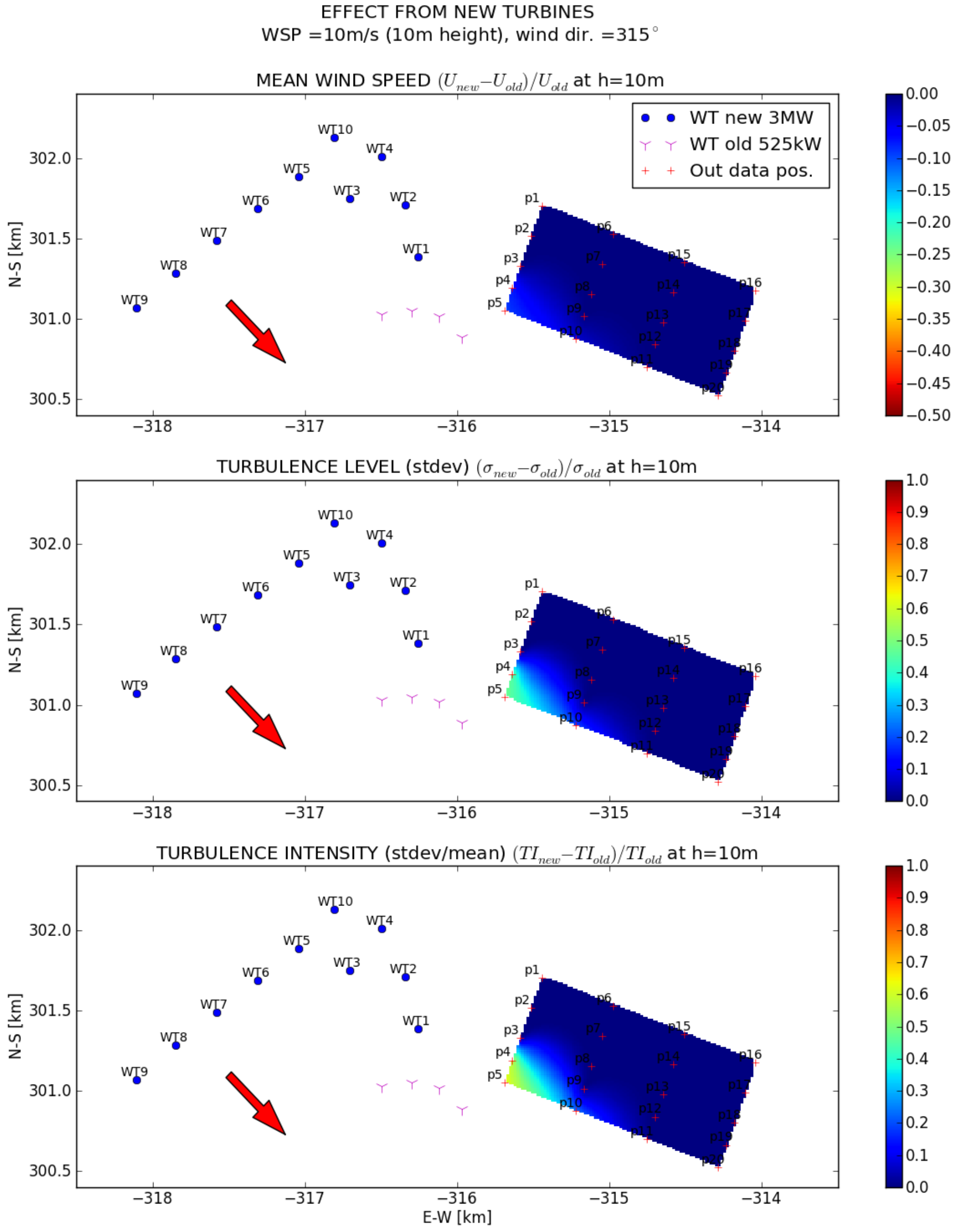

Figure 37. Wake effects from the new planned 3MW turbines relative to the existing wind conditions at 10m/s (10m height) and a wind direction of 315°. From top: relatively added mean wind speed [-], relatively added turbulence standard deviation [-], relatively added turbulence intensity [-].

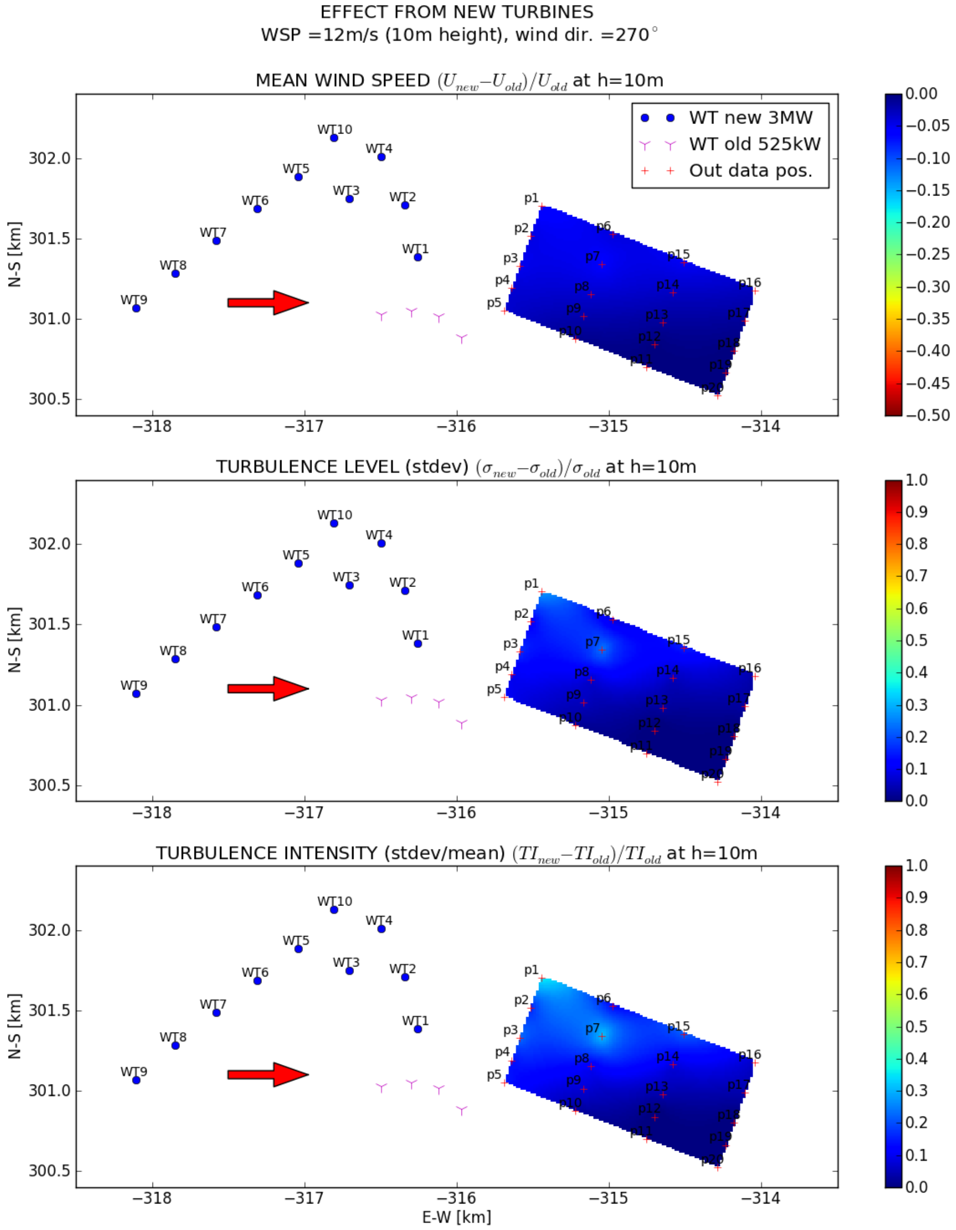

Figure 38. Wake effects from the new planned 3MW turbines relative to the existing wind conditions at 12m/s (10m height) and a wind direction of 270°. From top: relatively added mean wind speed [-], relatively added turbulence standard deviation [-], relatively added turbulence intensity [-].

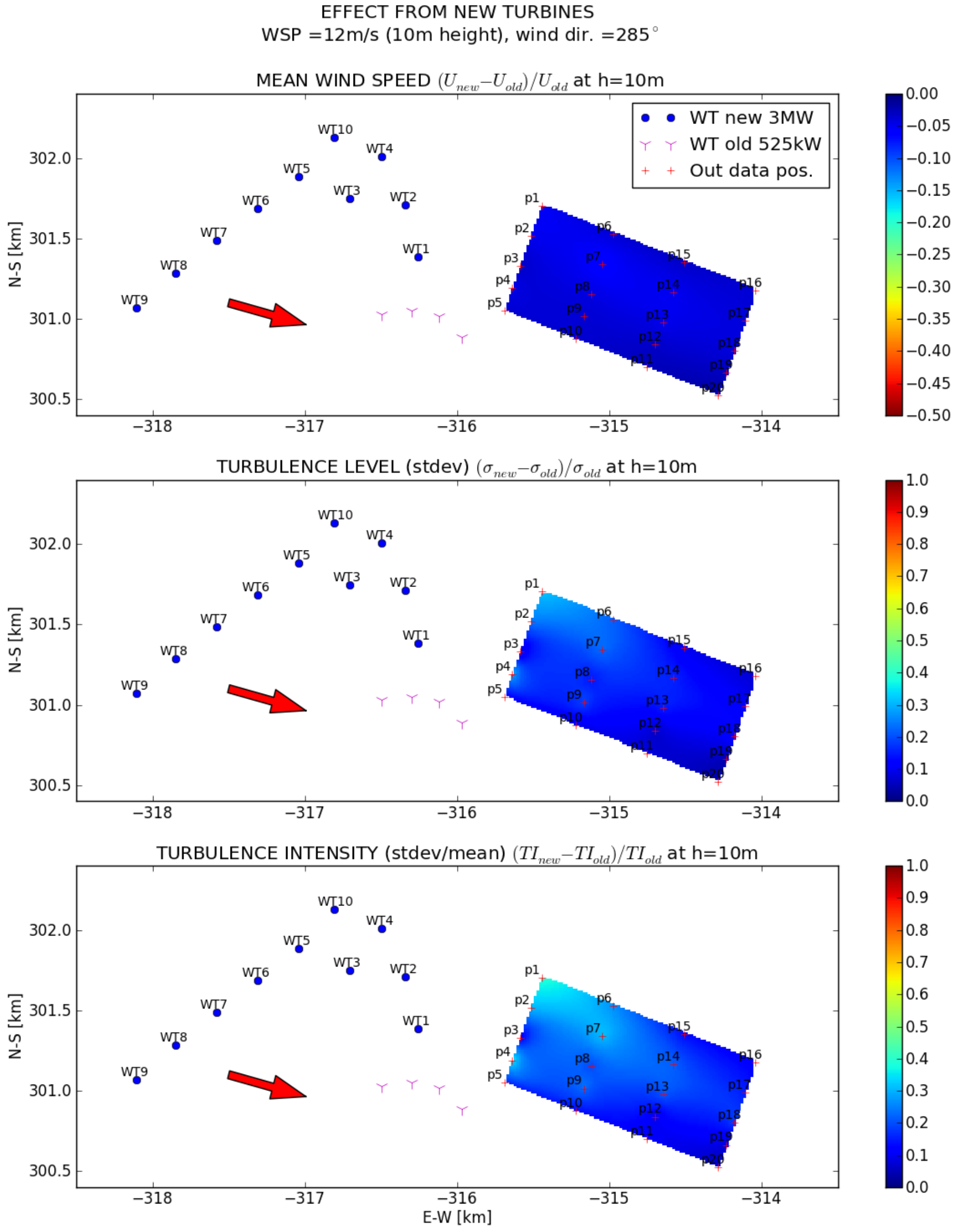

Figure 39. Wake effects from the new planned 3MW turbines relative to the existing wind conditions at 12m/s (10m height) and a wind direction of 285°. From top: relatively added mean wind speed [-], relatively added turbulence standard deviation [-], relatively added turbulence intensity [-].

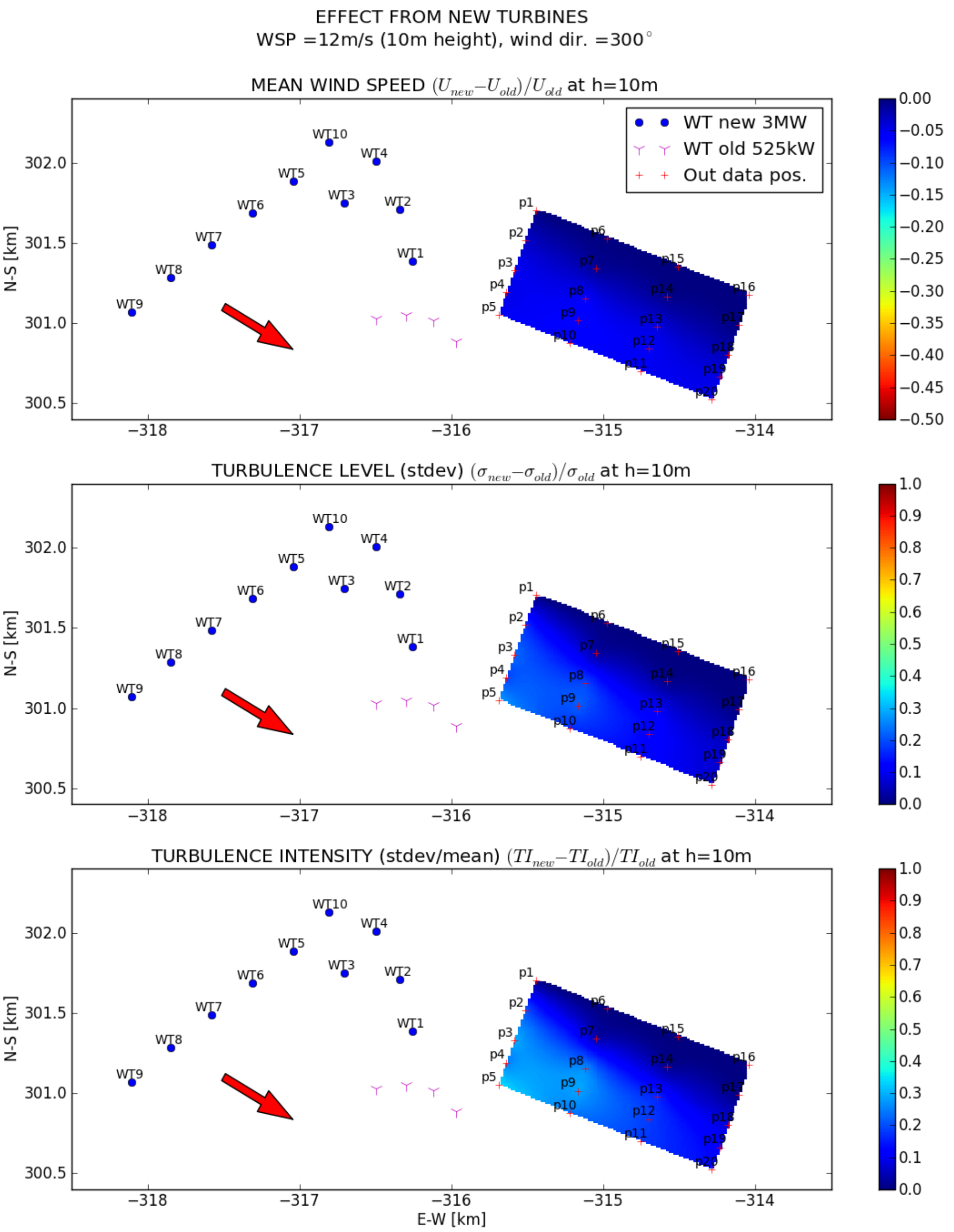

Figure 40. Wake effects from the new planned 3MW turbines relative to the existing wind conditions at 12m/s (10m height) and a wind direction of 300°. From top: relatively added mean wind speed [-], relatively added turbulence standard deviation [-], relatively added turbulence intensity [-].

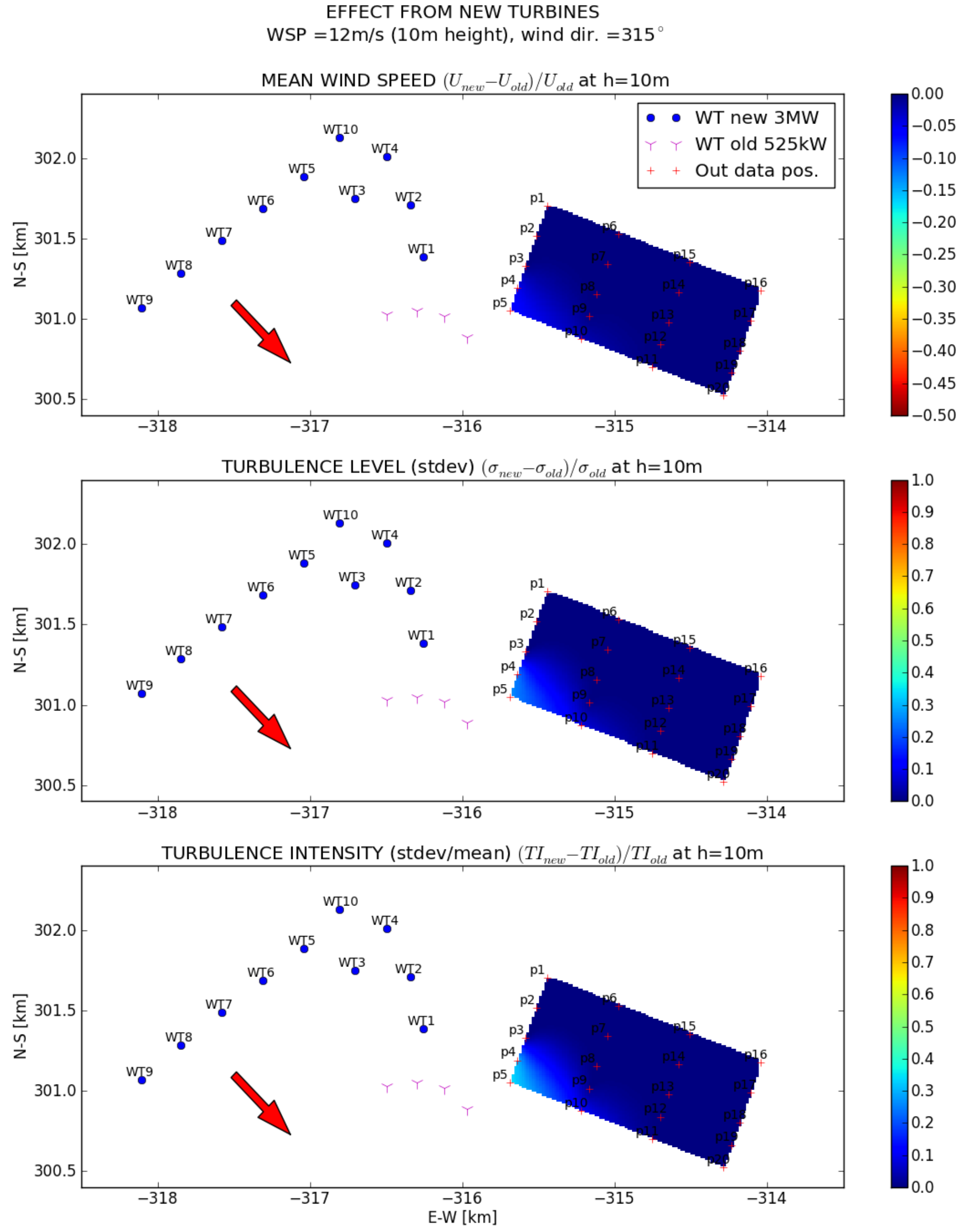

Figure 41. Wake effects from the new planned 3MW turbines relative to the existing wind conditions at 12m/s (10m height) and a wind direction of 315°. From top: relatively added mean wind speed [-], relatively added turbulence standard deviation [-], relatively added turbulence intensity [-].

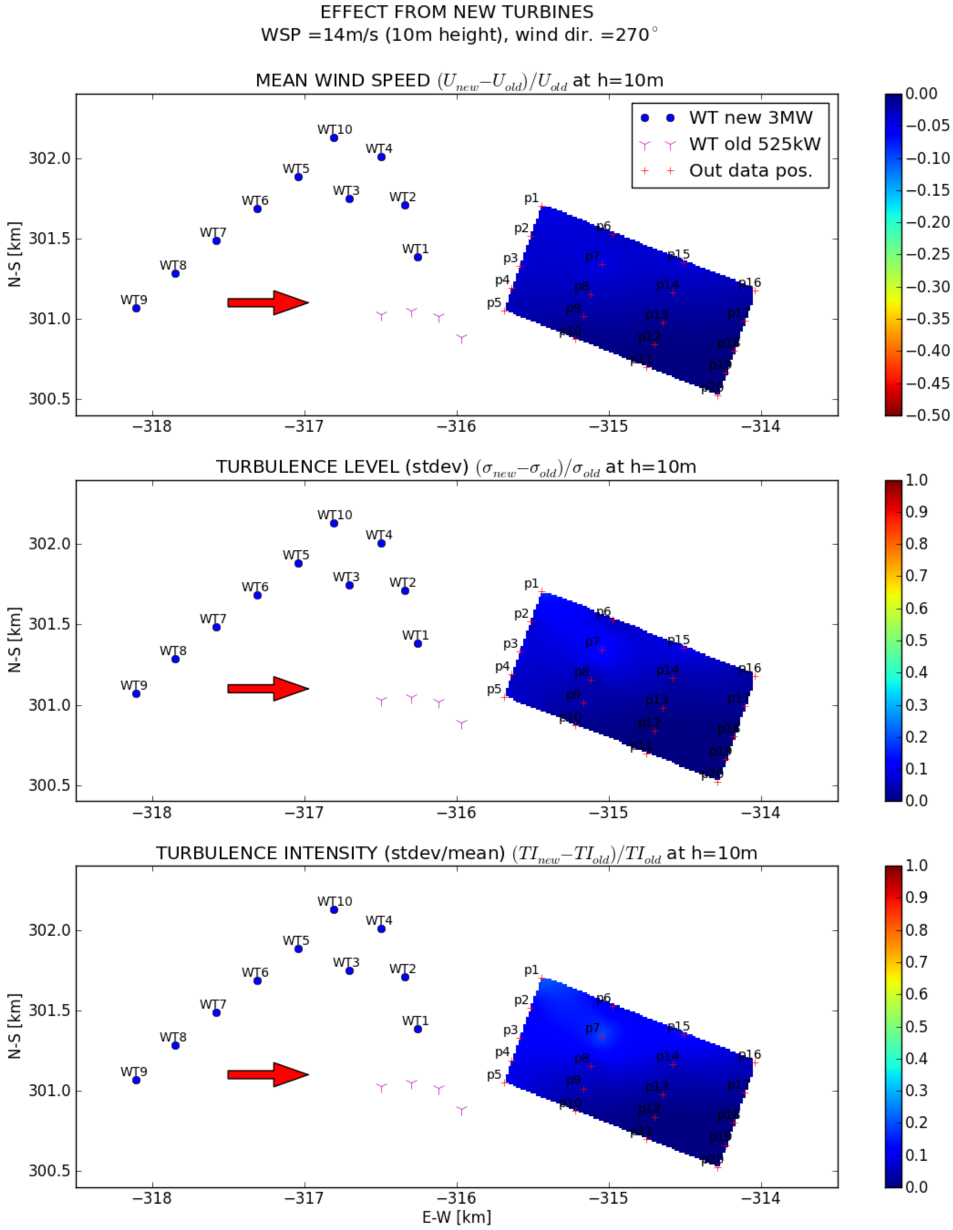

Figure 42. Wake effects from the new planned 3MW turbines relative to the existing wind conditions at 13m/s (10m height) and a wind direction of 270°. From top: relatively added mean wind speed [-], relatively added turbulence standard deviation [-], relatively added turbulence intensity [-].

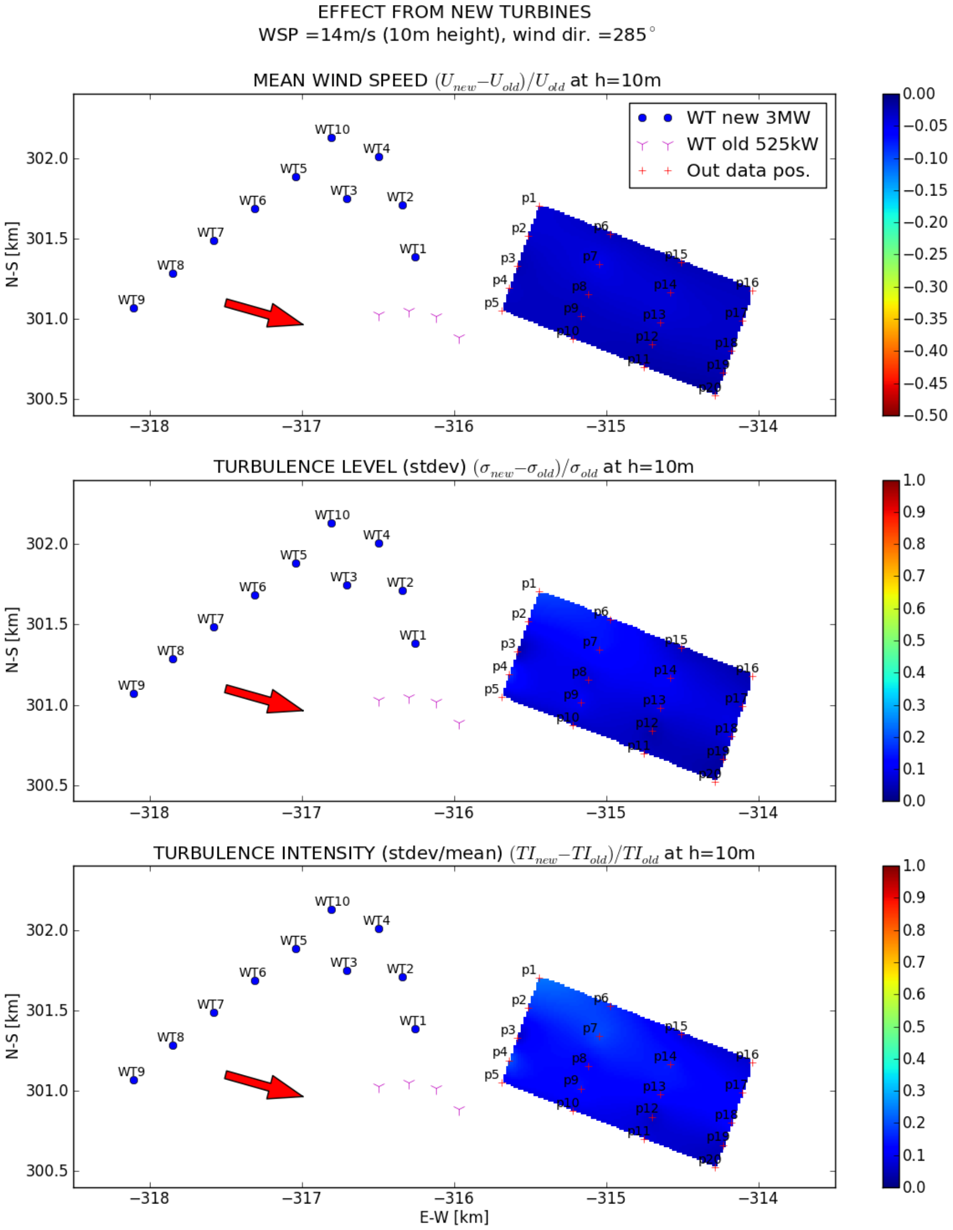

Figure 43. Wake effects from the new planned 3MW turbines relative to the existing wind conditions at 14m/s (10m height) and a wind direction of 285°. From top: relatively added mean wind speed [-], relatively added turbulence standard deviation [-], relatively added turbulence intensity [-].

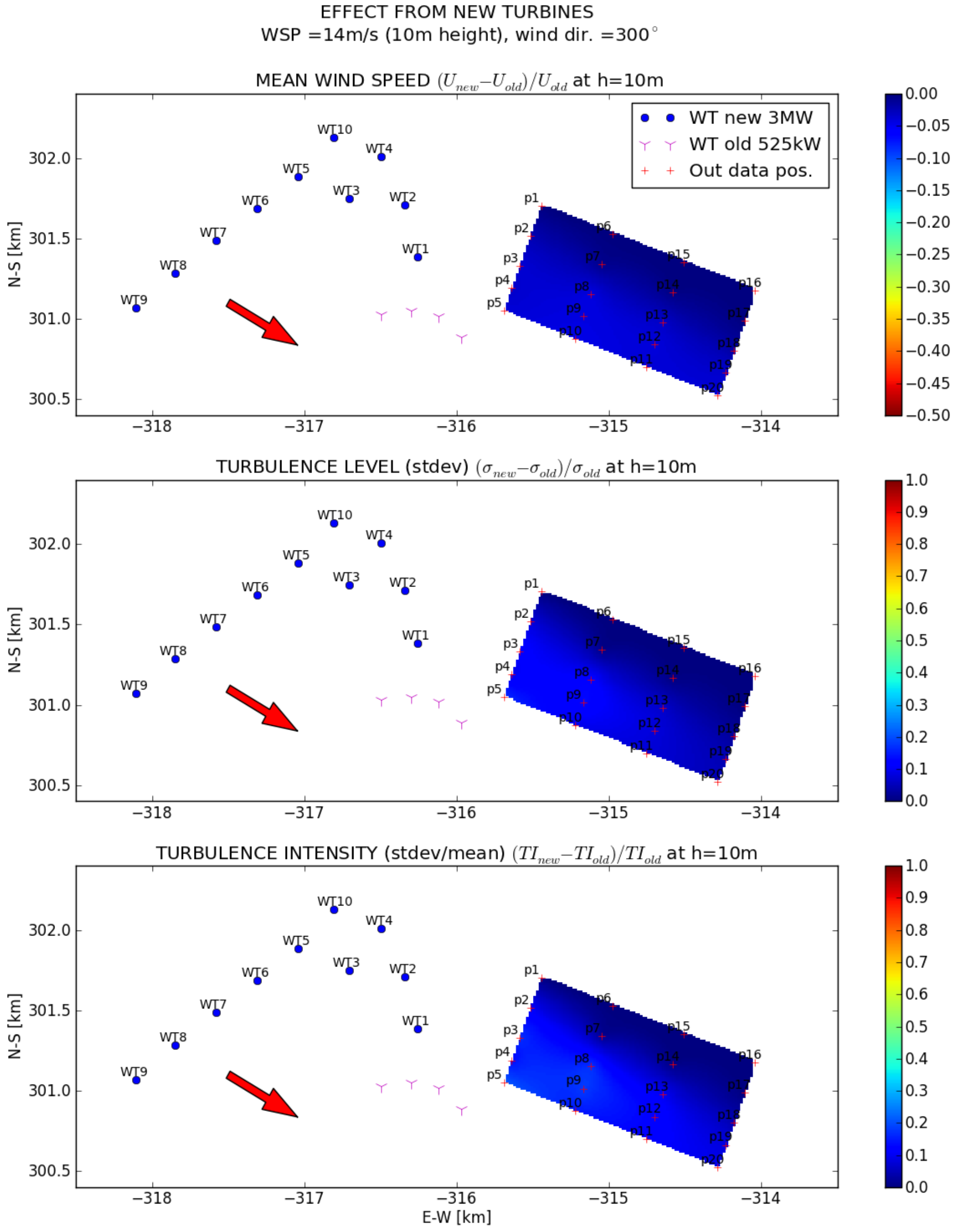

Figure 44. Wake effects from the new planned 3MW turbines relative to the existing wind conditions at 14m/s (10m height) and a wind direction of 300°. From top: relatively added mean wind speed [-], relatively added turbulence standard deviation [-], relatively added turbulence intensity [-].

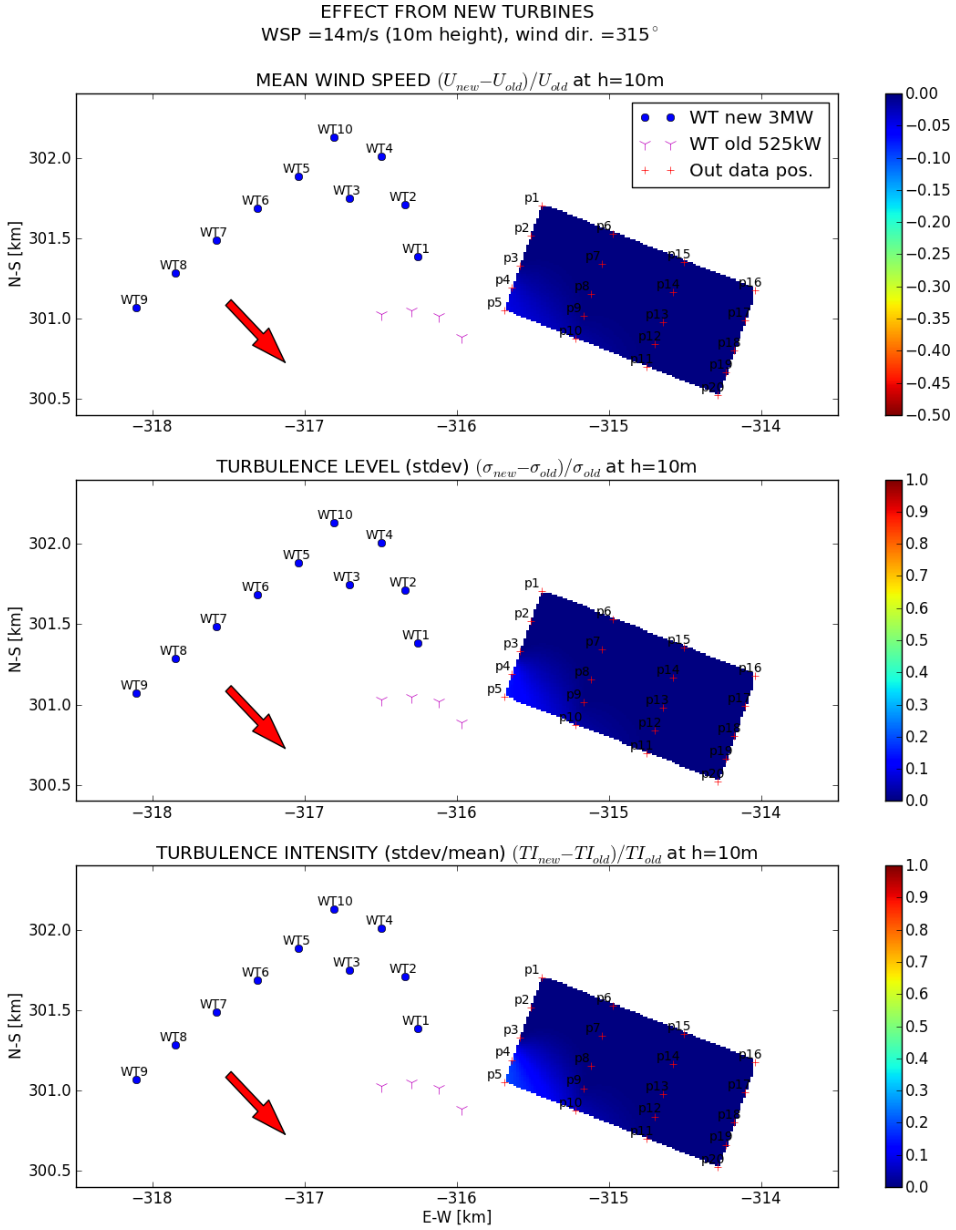

Figure 45. Wake effects from the new planned 3MW turbines relative to the existing wind conditions at 14m/s (10m height) and a wind direction of 315°. From top: relatively added mean wind speed [-], relatively added turbulence standard deviation [-], relatively added turbulence intensity [-].

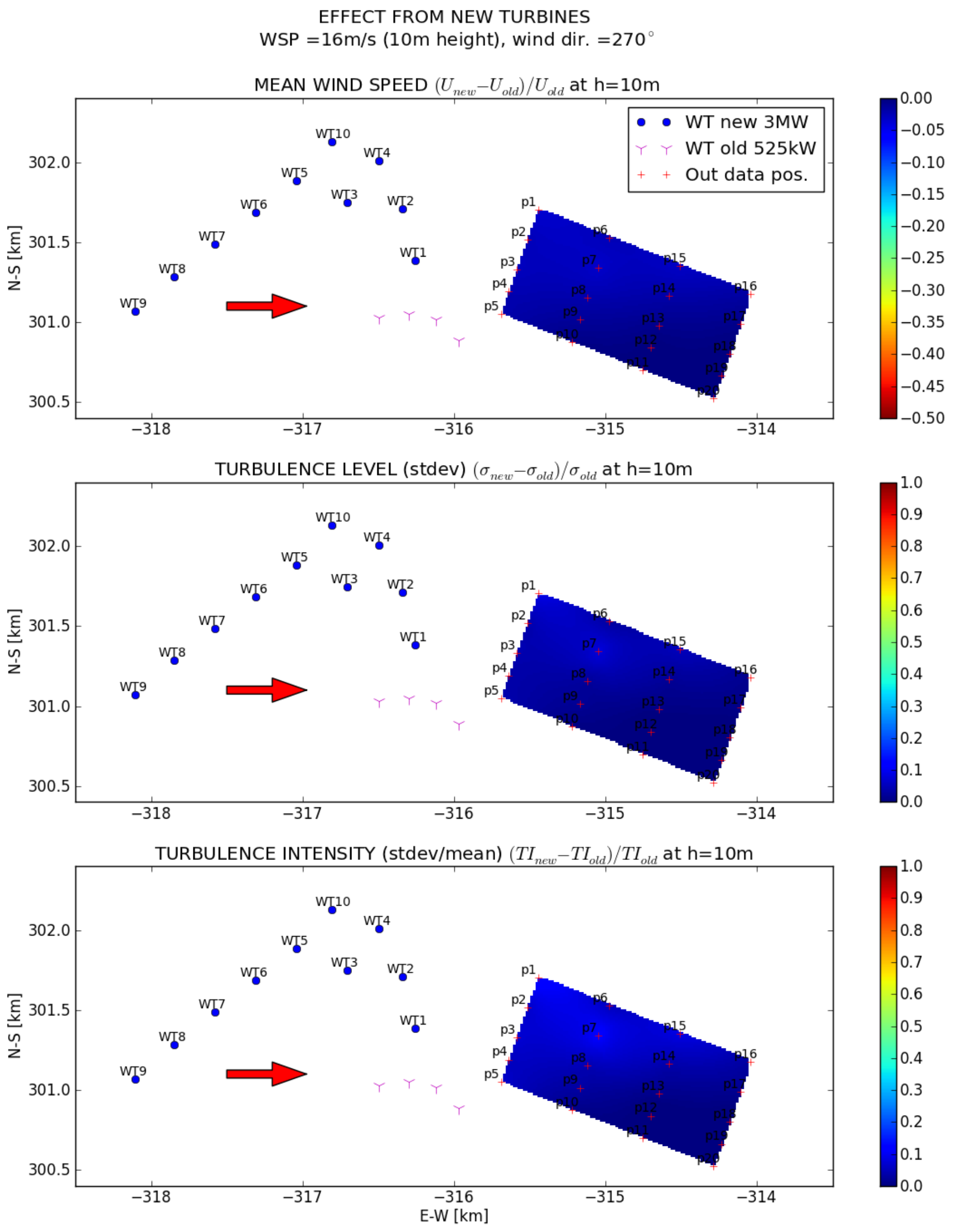

Figure 46. Wake effects from the new planned 3MW turbines relative to the existing wind conditions at 16m/s (10m height) and a wind direction of 270°. From top: relatively added mean wind speed [-], relatively added turbulence standard deviation [-], relatively added turbulence intensity [-].

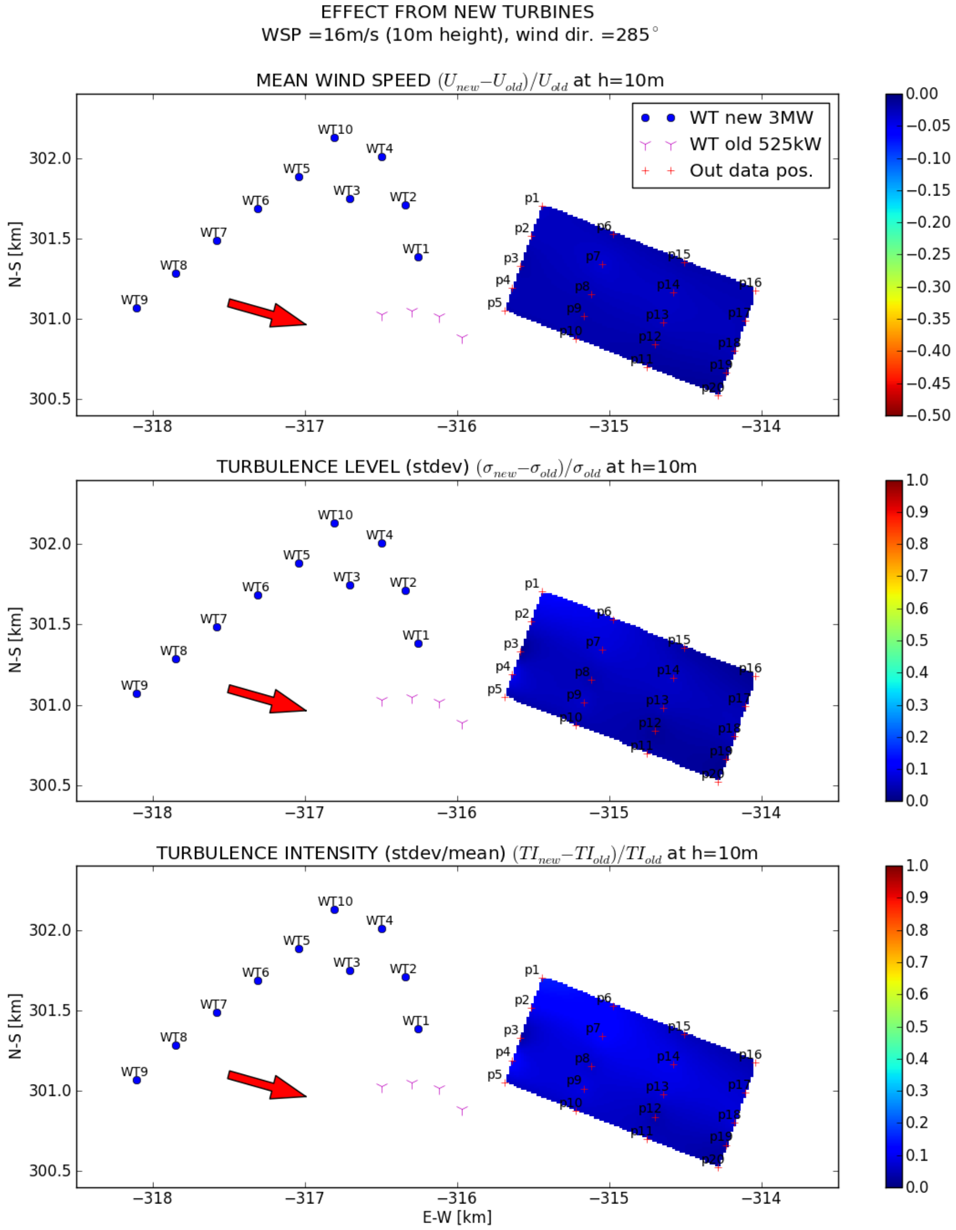

Figure 47. Wake effects from the new planned 3MW turbines relative to the existing wind conditions at 16m/s (10m height) and a wind direction of 285°. From top: relatively added mean wind speed [-], relatively added turbulence standard deviation [-], relatively added turbulence intensity [-].

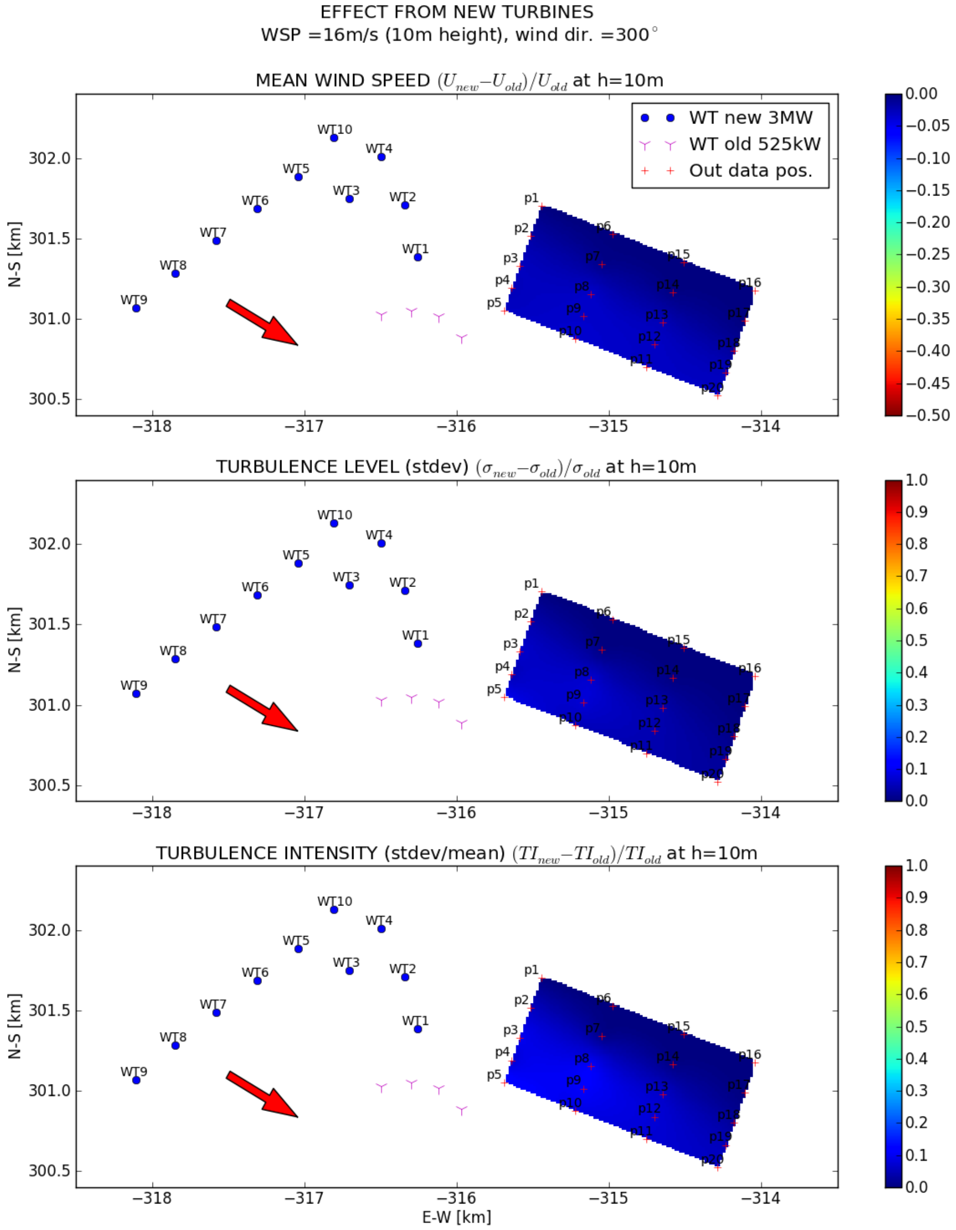

Figure 48. Wake effects from the new planned 3MW turbines relative to the existing wind conditions at 16m/s (10m height) and a wind direction of 300°. From top: relatively added mean wind speed [-], relatively added turbulence standard deviation [-], relatively added turbulence intensity [-].

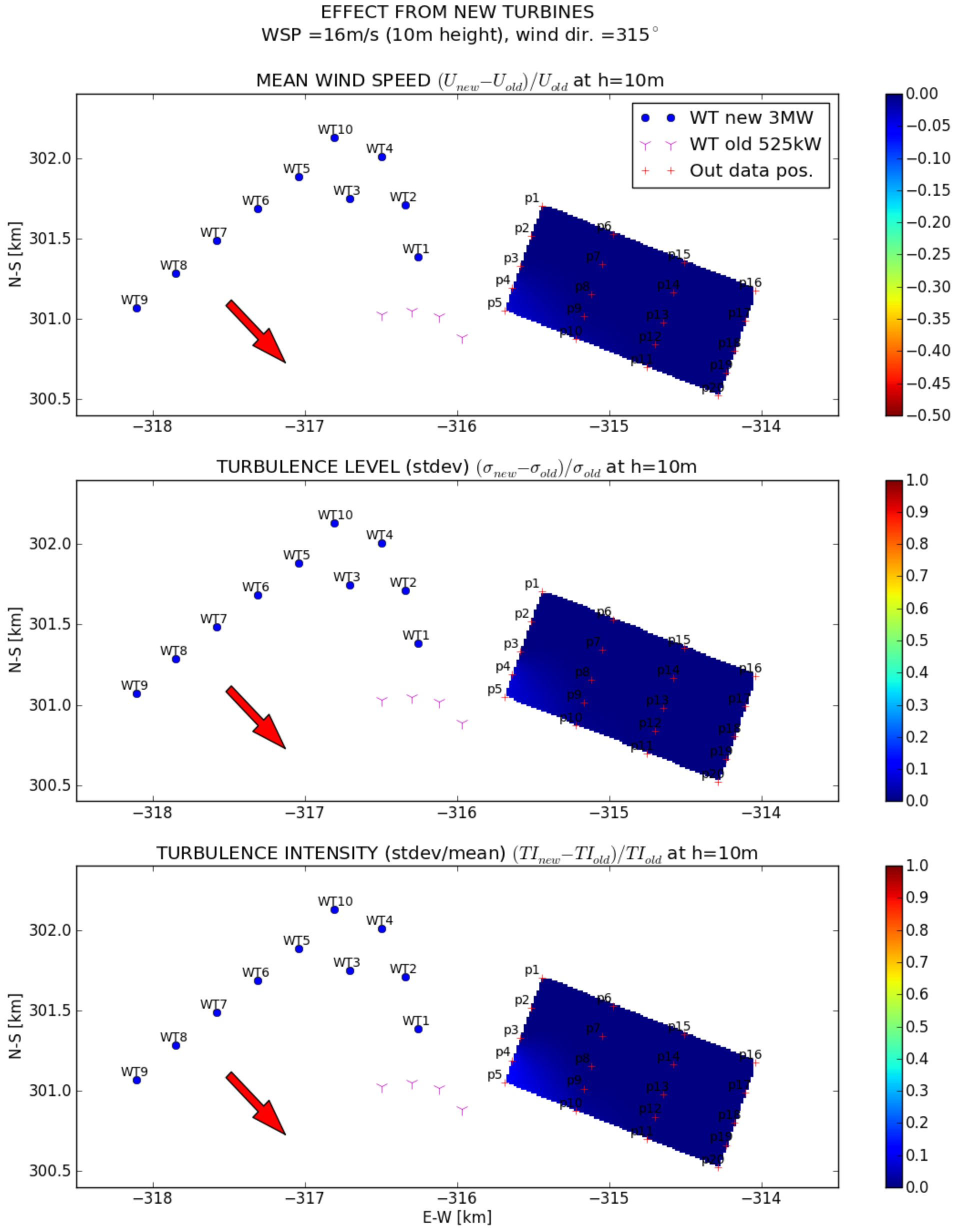

Figure 49. Wake effects from the new planned 3MW turbines relative to the existing wind conditions at 16m/s (10m height) and a wind direction of 315°. From top: relatively added mean wind speed [-], relatively added turbulence standard deviation [-], relatively added turbulence intensity [-].

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